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The role of visual spatial frequency channels in the global precedence effect

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THE ROLE OF VISUAL SPATIAL FREQUENCY CHANNELS IN THE GLOBAL PRECEDENCE EFFECT.

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CANDIDATE'S CERTIFICATE

I certify that the thesis entitled The Role of Visual Spatial Frequency Channels in the Global Precedence Effect, and submitted for the degree of Master of Arts (Honours), is the result of my own research, except where otherwise acknowledged, and that this thesis (or any part of the same) has not been submitted for a higher degree to any other university or institution.

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ABSTRACT.

Many studies have found that the global elements of hierarchically organized stimuli are processed more quickly than the local elements. This is known as the global precedence effect (GPE). It has been suggested that this reflects the activities of two visual sub-systems: a fast-transmitting sub-system sensitive to low spatial frequencies, and a slow-transmitting sub-system sensitive to high spatial frequencies.

The present series of experiments investigates the role of these spatial frequency channels in the GPE by manipulating factors that are known to affect these channels to see if they also have a predictable effect on the GPE. These factors include controlling the size, presentation position and visibility of stimuli, varying the colour of stimuli, and adapting the subject to a coloured grating prior to stimulus presentation.

It is concluded that the GPE is a reflection of lower-order visual processes. However, it is argued that the inconsistency effect, in which the identification of the local element is interfered with by an inconsistent global element, is produced by a separate higher-order cognitive process.

CONTENTS.

CHAPTER 1.

1. INTRODUCTION.

1.1 Aims.

The research to be reported here attempts to relate the known temporal properties of spatial frequency channels to the global precedence effect (GPE) that was studied in detail by Navon (1977). The general aim is to determine the extent to which the GPE and the accompanying inconsistency effect can be explained in terms of low-level visual processes such as spatial frequency channels, and the extent to which higher-order cognitive mechanisms need to be invoked to explain the data.

1.2 The global precedence effect.

One of the most fundamental issues in the research of visual processes is the question of the temporal order of the processing of visual information: does the visual system establish the global aspects of a scene before analysing the local detail, or does it begin with the details and then construct the global scene from there ?

Some theorists have suggested models of processing in which the various details or features of objects, such as lines, curves, corners and intersections, are identified by visual feature-detection mechanisms until enough information has been built up to identify the objects. This position has its origin in the structuralist school of psychology. Structuralists believed that the perception of a scene was achieved through the building up of a collection of elementary sensations, such as colour and brightness (Titchener, 1915). Perception of whole forms was thought to be achieved through learned associations between these elementary sensations. Theories of this type imply local-to-global processing of visual information.

More recent local-to-global models of visual processing have proposed the existence of feature-detecting mechanisms in the visual system, each responsible for detecting a particular type of feature in the stimulus. For example, the recognition of the letter "H" might require the detection of individual features (such as the two vertical bars, the horizontal bar, and the two intersections of the horizontal and vertical bars) by the appropriate feature-detecting mechanisms (e.g., Gibson, 1965; Selfridge, 1959). There is some physiological evidence of such feature-detecting mechanisms. Hubel and Wiesel (1962, 1965, 1968) have found cortical cells that respond to basic stimuli such as bars, edges and corners. However, subsequent investigations have revealed that some single cortical cells respond maximally only to complex stimuli (Gross, 1975), suggesting that "features" need not necessarily be elementary or "local" in nature.

Other theorists have emphasised the primacy of the global aspects of the scene in perception. This position is ultimately derived from the ideas of the Gestalt school of psychology (e.g., Koffka, 1935). Gestalt theorists believed that the whole of an observed scene is immediately represented as a corresponding pattern of electrical activity in the brain. The perception of individual forms or patterns within the scene was thought to be achieved by the use of certain grouping or organisational principles in the visual system, including similarity, proximity and closure. These grouping principles were said to allow figures to be distinguished from the ground, and from other figures in the scene. Theories of this type imply global-to-local processing of visual information.

It has frequently been reported that the global aspects of a visual stimulus are identified more quickly than the local aspects of the stimulus (Breitmeyer, 1975; Broadbent, 1977; Navon, 1977; Navon & Norman, 1983; Petersik, 1978). One of the most popular paradigms for studying this phenomenon has become known as the global precedence effect (GPE). Investigations into this effect, following the example of Navon (1977), have typically used compound figures as stimuli. In Navon's experiments human subjects are shown compound letter stimuli: large ("global") alphabetic letters composed of smaller ("local") letters (Figure 1). The small and large letters may be consistent or inconsistent with each other. For example, subjects may be shown a large composite H constructed from a number of small Hs (consistent), or a large composite H made of small Ss (inconsistent). In the global-level identification test condition, subjects are instructed to respond as soon as they can identify the larger letter as either an H or S. In the local-level identification test condition they are asked to respond to the small component Ss and Hs. It was originally found (Navon, 1977) that subjects were significantly faster at responding to the global composite than to the local component letters. This is the standard global precedence effect (GPE).

In addition, Navon's subjects identified the local-level letters more slowly when the global-level letter was inconsistent with them than when the global and local letters were consistent with each other. On the other hand, the speed of identification of the global letter was not affected by the consistency or inconsistency of the local letters. This phenomenon is the inconsistency effect (IE).

There has been some debate about whether these effects are a reflection of the operation of low-level visual processes or of some higher-level cognitive processes such as attention. One theory in favour of low-level processing suggests that the transient and sustained visual sub-systems may be involved in global-to-local processing (eg., Sestokas & Lehmkuhle, 1986; Sestokas, Lehmkuhle & Kratz, 1987). In summary, this theory proposes that the visual system processes low spatial frequency stimuli (i.e., large objects or over-all shapes) via the fast transient sub-system, and high spatial frequency stimuli (i.e., small objects or fine detail) via the slower sustained sub-system. These processes will be described in detail in the next section.

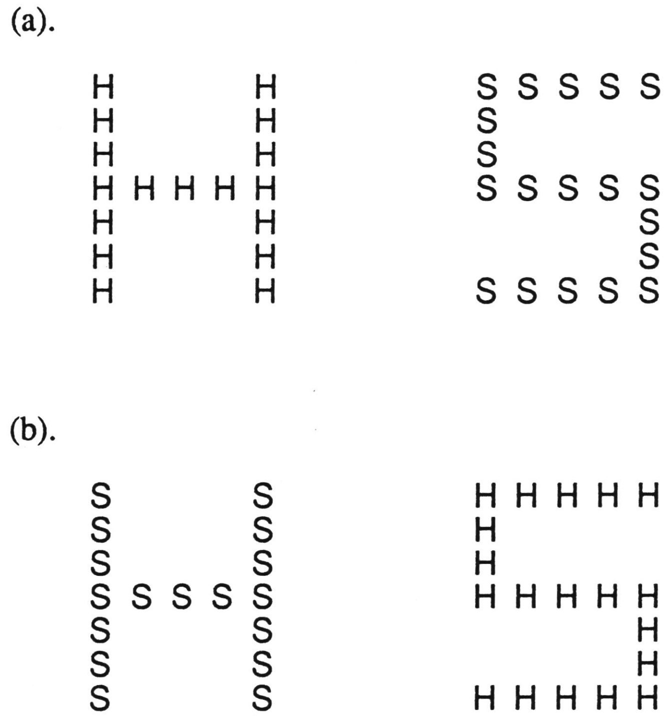


Figure 1. Compound letter stimuli similar to those used by Navon (1977). Stimuli with consistent global and local elements are shown at (a), and stimuli with inconsistent global and local elements are shown at (b). (Not to scale.)

1.3 Visual spatial frequency channels.

1.3.1 The concept of spatial frequency.

It has long been known that sound is conveyed as vibrations through the air and the inner mechanisms of the ear. These vibrations take the form of waves of alternately compressing and decompressing molecules in the sound-conveying medium. The most basic type of sound is the pure tone. The pattern of vibration produced by the pure tone can be described graphically as a sine wave, with the pitch of the tone represented as the frequency of the wave. Most sounds, however, are complex tones that can only be fully described by complex wave-forms consisting of an additive mixture of sine waves of various frequencies, amplitudes and phases.

More recently, visual stimuli have also been described in terms of complex wave-forms made up of a mixture of simple wave-forms of different frequencies, amplitudes, phases and orientations. For example, areas of relative lightness and darkness in the visual scene can be described in terms of peaks and troughs in the amplitude of the wave-forms. Similarly, the size of objects in the scene can be described in terms of spatial frequencies within the wave-forms. In simple terms, this means that all objects that appear in the visual scene may be described as having particular spatial frequencies. Large shapes can be said to have a low spatial frequency because only a small number of them can fit within a given area of space. Conversely, small shapes (or fine detail on large shapes) could be regarded as high spatial frequency, because a large number of them can fit within a given area of space.

1.3.2 Spatial frequency in the visual system.

It has been well established that the visual systems of humans and other mammals contain cells which are sensitive to stimuli of a particular spatial frequency. Studies in this area typically use gratings, the simplest of spatial frequency stimuli, and they measure responses to these stimuli by physiological or psychophysical methods. These gratings are sets of regularly alternating dark and light bars or stripes, all of the same orientation. One of the most common types of grating used in these experiments is the sine-wave grating, so-called because a graph of the repeated gradual rise and fall of luminance as you move across the grating takes the form of a sine wave. The amount of contrast between the lightest and darkest areas of the grating is represented on the luminance graph of the grating by the depth (amplitude) of the sine wave. A high spatial frequency sine-wave grating appears to the observer as a set thin blurry-looking stripes, while a low spatial frequency grating appears as a set of thick stripes. Square wave gratings, which are actually composites of a number of different sine waves and which the change abruptly in luminance between the light and dark stripes, are also often used as stimuli.

1.3.3 Psychophysical evidence of spatial frequency channels.

Campbell and Robson (1968) originally proposed that the visual system contains a number of independent spatial frequency-specific channels. Using psychophysical methods and sine-wave gratings as stimuli, they determined that subjects had different contrast thresholds for gratings of different frequencies. (Contrast threshold is the amount of contrast between the lightest and darkest parts of the grating that is needed for the subject to see the grating.) Furthermore, using compound grating stimuli composed of more than one spatial frequency, they found that subjects could detect each spatial frequency component only when the contrast of the compound grating stimulus had reached the contrast threshold for that particular spatial frequency.

Campbell and Robson (1968) have suggested that the visual system uses its spatial frequency channels to perform a Fourier analysis, or something like it, on the visual scene. Fourier analysis is a mathematical technique that allows complex wave-forms to be described in terms of their basic sine-wave components. A Fourier analysis of a square wave, for example, reveals that it may be decomposed into a sine wave called the fundamental which is the same spatial frequency as the final square wave, plus a sine wave which has three times the frequency and one-third the amplitude of the fundamental (the "third harmonic"), plus another sine wave which has five times the frequency and one-fifth the amplitude of the fundamental (the "fifth harmonic"), and so on. More complex wave-forms may be composed of sine waves of many different spatial frequencies, amplitudes, phases and orientations. The application of Fourier theory to vision presupposes that the visual world - its rises and falls of luminance across space - is a set of complex wave-forms which can be analyzed on the basis of its component sine-waves by channels in the visual system.

Further evidence for the existence of spatial frequency channels has been found in other psychophysical studies. Several studies have demonstrated that adapting to a grating of a particular spatial frequency (by staring at it for a long time) subsequently raised the contrast threshold for the detection of gratings of that and similar frequencies, but did not affect thresholds for the detection of gratings of other frequencies (Blakemore & Campbell,1969; Blakemore, Nachmias & Sutton, 1970; Movshon & Lennie, 1979; Pantle & Sekuler, 1968). It seems that the adaptation had fatigued the channel which would normally convey information about that particular spatial frequency, making it more difficult to detect. In another study, Graham and Nachmias (1971) compared the contrast thresholds for pairs of compound gratings. Each of the two compound gratings was made up of combinations of the same spatial frequencies, but with different relative phases. This meant that one of the resulting compound gratings contained some very bright and some very dark bars, while the other compound grating contained bars of more or less moderate brightness. It might be expected that the detection of the first of these gratings would have a lower contrast threshold than the second, because of the greater differences in luminances it contained. However, they found that the two types of compound grating had equal contrast thresholds, apparently determined by their identical spatial frequency components.

1.3.4 Physiological evidence of spatial frequency channels.

Physiological evidence about the visual system has come mostly from animal studies, usually using cats or monkeys as subjects. Such studies typically involve the placing of very fine microelectrodes into the relevant section of the visual pathway. These electrodes record the responses of single cells in that area when the subject is presented with various visual stimuli.

The main visual pathway in humans and other mammals involves the passage of information through three structures. The first of these is the retina, the layers of cells lining the rear wall of the eye. Information collected by these retinal cells is relayed via the optic nerve and optic tract to a pair of brain structures, the lateral geniculate nuclei (LGN). From here, the information is sent to the visual cortex at the rear of the brain. Much of the evidence about the way information is conveyed through this pathway suggests that there are two sub-systems involved: the transient and sustained sub-systems.

The retinal ganglia.

Firstly, the retina contains neural cells (known as ganglion cells) which gather information from a number of retinal receptor cells. These receptor cells form the receptive field of the ganglion cell, with this receptive field usually being approximately circular in shape. The firing rate of some of the ganglion cells will increase if light falls anywhere in the centre of their receptive fields, but the firing rate will decrease if light falls in the ring-shaped area around the edge of the receptive field. (This phenomenon is known as lateral inhibition.) Ganglion cells such as these are known as "on"-centre, "off"-surround cells. They respond most vigorously to a stimulus which causes light to fall on the whole excitatory central area of the receptive field, and no light to fall on the inhibitory ring area. For the other ganglion cells, known as "off"-centre, "on"-surround cells, the whole situation is reversed (Kuffler, 1953). The size of these receptive fields varies according to their position in the retina. Those found in the centre of the retina, around the fovea, are usually smaller than those in the peripheral areas of the retina (Wiesel & Hubel, 1960).

However, the most important difference between ganglion cells for the present discussion is the distinction between M and P ganglion cells which have been found in monkeys, and similar cells found in the cat known as Y and X cells, respectively (Shapley & Perry, 1986). (The monkey M and P pathways are more likely to resemble pathways in human vision, but more work has been done on the cat X and Y pathways. While the cat X and Y pathways may give us valuable clues about how human visual pathways work, it is important to note that cat X and Y pathways appear not to be identical with monkey P and M pathways. Information about cat X and Y pathways must therefore be applied to human vision with caution.)

M and P cells have also been called transient and sustained cells, respectively. Transient (M or Y) cells tend to respond briefly to changes in light level, such as a light stimulus that is moving or flickering. Sustained (P or X) cells respond continuously to the presence of a stationary or near-stationary stimulus (Cleland, Dubin & Levick, 1971, with cats; Enroth-Cugell & Robson, 1966, with cats). M cells transmit information more quickly than P cells, and generally have larger receptive fields. M cells are able to respond to stimuli of lower contrast than P cells (Kaplan, Shapley & Purpura, 1988, with monkeys). Each P cell usually responds only to stimuli of a particular preferred colour, whereas M cells do not seem to have a colour preference (Lennie, Trevarthen, Waessle & Van Essen, 1990).

Ganglion cells could operate as crude spatial frequency analysers (eg., Enroth-Cugell & Robson, 1966). For example, when presented with a grating stimulus each ganglion cell's response would be determined by how well each bar of the grating fitted the cell's receptive field. The best response would be produced in those cells which had an excitatory receptive field centre the same width (and luminance polarity) as each bar in the grating, although the cell's response would be slightly suppressed by the bar crossing part of the inhibitory surround. A cell with a larger receptive field would respond more weakly to the same grating because a smaller proportion of its excitatory field centre would be stimulated, and a cell with a smaller receptive field would also respond more weakly because the grating's bar would be encroaching even further into the inhibitory surrounding area of the receptive field. If this is the case, we would expect those ganglion cells with large receptive fields (mostly M cells) to respond best to low spatial frequency stimuli, and ganglion cells with small receptive fields (mostly P cells) to respond best to high spatial frequency stimuli. As we have seen above, M cells transmit information more quickly than P cells, so we might predict that information about low spatial frequency stimuli will be transmitted faster than information about high spatial frequency stimuli.

The lateral geniculate nuclei.

A similar distinction has also been found at the next stage of information processing in the LGN. LGN cells also have roughly circular receptive fields in the retina, and these receptive fields may be "on"-centre, "off"-surround or "off"-centre, "on"-surround (Maffei & Fiorentini, 1972). The LGN contains layers of two distinct types of cell bodies which appear to have properties similar to those of the M and P retinal ganglion cells (Cleland, Dubin & Levick, 1971, with cats; Livingstone & Hubel, 1988; Schiller & Malpeli, 1978, with monkeys). The larger LGN cells (magno cells) tend to have larger receptive fields than the smaller LGN cells (parvo cells). The magno cells transmit information faster than the parvo cells (Sestokas & Lehmkuhle, 1986; Sestokas, Lehmkuhle & Kratz, 1987, with cats). Magno cells respond best to moving stimuli, while parvo cells prefer stationary or slowly moving stimuli. Magno cells have no colour preference, while parvo cells usually respond only to stimuli of a particular preferred colour (Dreher, Fukada & Rodieck, 1976, with monkeys; Wiesel & Hubel, 1966, with monkeys). However, there is evidence that long-wavelength (red) light can inhibit magno cells (Dreher, Fukuda & Rodieck, 1976; Schiller & Malpeli, 1978, with monkeys). Magno cells are more sensitive to low-contrast stimuli than parvo cells (Shapley, Kaplan & Soodak, 1981, with monkeys). In short, magnocellular LGN cells seem to correspond to M (transient) ganglion cells, and parvocellular LGN cells seem to correspond to P (sustained) ganglion cells.

Since the properties of these LGN cells are so similar to those of retinal ganglion cells, it may be possible that LGN cells also work as crude spatial frequency analysers (eg., Campbell, Cooper & Enroth-Cugell,1969; Campbell, Cooper, Robson & Sachs, 1969). In this case the magno cells would favour low spatial frequency stimuli and parvo cells would favour high spatial frequencies.

The visual cortex.

At the third stage of processing, in the visual cortex, we also find cells that have either "sustained" or "transient" characteristics. Unlike retinal ganglion and LGN cells, however, these cortical cells do not have simple round receptive fields. Each will generally respond only to a narrow range of stimuli, such as edges or bars of a particular width, aligned at a particular orientation. The more a stimulus deviates from a cell's preferred stimulus attributes - too wide, too narrow, at the wrong angle - the weaker will be that cell's response (Hubel & Wiesel, 1962, 1965, 1968, with cats and monkeys).

Some of these cortical cells, known as simple cells, have relatively small receptive fields and respond best when a stimulus of the preferred type is presented in one particular area of the subject's visual field. Like retinal ganglion and LGN cells, the receptive fields of simple cells are divided into excitatory ("on") and inhibitory ("off") regions. Simple cells also prefer slow moving or stationary stimuli, although they will respond with modulated bursts of firing if the bars of a moving grating drift across their receptive fields. Other cortical cells, called complex cells, have larger receptive fields without definite excitatory or inhibitory regions, and will respond to their preferred type of stimulus when it is presented anywhere in a relatively large area of the subject's visual field. Complex cells usually prefer moving stimuli, and will often prefer stimuli moving in one particular direction (Hubel & Wiesel, 1965, 1968, with cats and monkeys; Movshon, 1975, with cats). Each simple cell also appears to be finely tuned to stimuli within a narrow range of spatial frequencies, while individual complex cells will respond to a wider range of spatial frequencies (Maffei & Fiorentini, 1973, with cats). Furthermore, the preferred spatial frequency of a cortical cell is correlated with the size of that cell's receptive field (Maffei & Fiorentini, 1977, with cats). As simple cells have relatively small receptive fields they are likely to be more sensitive to higher spatial frequency stimuli. These distinctions between simple and complex cells suggest that two separate sub-systems also exist at the cortical level.

It has been suggested that simple and complex type cortical cells receive input from the parvo and magno pathways respectively (Livingstone & Hubel, 1988). According to this model, magno LGN cells project to layer 4Ca of the primary visual cortex, which in turn projects to layer 4B. Cells in this layer appear to be of the complex type, with each cell preferring stimuli of a particular orientation moving in a particular direction. Cells from this layer then project to higher visual areas concerned with perception of movement and stereo depth. Parvo LGN cells, on the other hand, project to layer 4Cb of the primary visual cortex and then to layers 2 and 3. Layers 2 and 3 contain clusters of cells known as blobs and interblobs. Interblob cells appear to be mostly of the simple cell type. They do not prefer stimuli moving in any particular direction, but they do prefer stimuli of a particular orientation and spatial frequency. The receptive fields of these cells are relatively small, so they would tend to favour relatively high frequency stimuli. The blob clusters contain cells which are sensitive to stimuli of either a particular colour or a particular brightness, but do not prefer particular orientations or spatial frequencies. It is thought that the non-colour-sensitive blob cells may receive some input from the magno pathways, while those that are colour-sensitive receive input from the parvo pathways (Livingstone & Hubel, 1988).

1.3.5 The connection between spatial frequency channels and the transient and sustained sub-systems.

It has been suggested that the magno/transient pathway, which seems to detect movement, depth and low spatial frequencies, may be involved in the initial separating of figure from ground in the visual scene. The slower parvo/sustained pathway, with its preference for higher spatial frequencies and colour and its ability to discriminate more finely between different stimulus orientations and spatial frequencies, could then analyse the finer detail of the scene (Breitmeyer, 1992; Livingstone & Hubel, 1988).

The information detailed in the previous section concerning the connection between spatial frequency channels and the transient and sustained sub-systems comes from animal studies. There is also considerable evidence about this connection from psychophysical studies involving human subjects (Breitmeyer, 1992; Kulikowski & Tolhurst, 1973; Tolhurst, 1973). Breitmeyer (1975), for example, had human subjects press a button as soon as they saw a grating flashed up on a screen. He found that they were significantly faster at responding to low frequency gratings than high frequency gratings. This finding conforms with the theory that information about low frequencies is transmitted via the relatively fast transient sub-system, and information about high frequencies is transmitted via the slower sustained system.

Similar results have been found by other researchers using a variety of psychophysical measures including reaction time (Lupp, Hauske & Wolf, 1976), visible persistence (Meyer & Maguire, 1977), and critical duration (Watson & Nachmias, 1977). There are also some physiological studies of human subjects, using cortical evoked potentials as a measure of transmission speed, which have reached the same conclusion (Parker & Salzen, 1977; Vassilev, Manahilov & Mitov, 1983; Vassilev & Stomonyakov, 1987.) It has been shown that these temporal differences in the perception of high and low spatial frequencies remain even when the different spatial frequencies are matched in apparent contrast with measures of reaction time (Breitmeyer, 1975; Lupp, Hauske & Wolf, 1976) and visible persistence (Bowling, Lovegrove & Mapperson, 1979).

Table 1.

Properties of the Sustained and Transient Visual Sub-Systems.

Sustained Sub-System	**Transient Sub-System.**
Most sensitive to high spatial frequencies.	Most sensitive to low spatial frequencies.
Most sensitive to low temporal frequencies, (i.e., stationary stimuli).	*Most sensitive to high temporal frequencies, (i.e., moving or flickering stimuli).*
Less sensitive to contrast.	Highly sensitive to low contrasts.
Is able to distinguish between colours.	*Is effectively "colour-blind", but may be inhibited by red light and enhanced by blue light.*
Slow transmission times.	Fast transmission times.
Responds throughout stimulus presentation.	*Responds at stimulus onset and offset.*
Predominates in central vision.	Predominates in peripheral vision.
Has relatively small receptive fields.	*Has relatively large receptive fields.*

The properties of the sustained and transient sub-systems, based on the above evidence, are summarised in Table 1.

In summary, the spatio-temporal interactions of the transient and sustained sub-systems seem to reflect a global-to-local order of visual information processing. The global, coarse configurational properties of the spatial stimulus are likely to be processed by fast-acting low spatial frequency mechanisms, and the local spatial details are subsequently processed by slower-acting high spatial frequency mechanisms. In other words, the visual system seems to process information about the "forest" before the "trees".

However, most work on spatial frequency channels and the transient-sustained dichotomy has been performed using highly artificial stimuli such as sine-wave gratings. Less research has been directed towards addressing questions about these processes with stimuli more natural than gratings. The GPE produced using compound figure stimuli may be able to fulfil this role.

1.4 Contradictory results in studies of the GPE.

However, some researchers have argued against the involvement of low-level visual mechanisms in the global precedence effect because some experiments have failed to find the standard GPE with certain stimulus configurations. Martin (1979) found that local-level letters may be identified more quickly than global-level letters if the compound letter stimulus is sparsely configured. She did this by reducing the number of local letters present in the global stimulus (Figure 2). If her results are robust, they have important implications for the role of spatial frequency channels in more complex tasks.

Analysis of her experiments, however, shows that she not only changed stimulus density but also stimulus size. For both the dense and the sparse stimulus configurations the global letter measured $4.1^{\circ} \times 2.8^{\circ}$ of visual angle. In the dense configuration the global letter was made up of $0.49^{\circ} \times 0.35^{\circ}$ local letters in a 7 x 5 letter matrix, while in the sparse configuration the size of the local letters was increased to $0.68^{\circ} \times 0.51^{\circ}$ in a 5 x 3 letter matrix. Kinchla and Wolfe (1979) have shown that the strength and direction of precedence effects can be affected by the retinal size of the stimuli. They demonstrated that the GPE appeared only when the compound letter was relatively small in visual angle. When the whole compound figure (both global and local elements) was made progressively larger, the GPE diminished and eventually reversed into an apparent local precedence effect. Antes and Mann (1984) made a similar finding using naturalistic stimuli. In this experiment a beach or farm scene represented the global level target, with a boat or tractor as the local level target. They found a standard GPE when the scene was 4° of visual angle, neither global nor local precedence when the scene was 8°, and local precedence when the scene was 16°. Consequently it is not clear whether stimulus sparsity or stimulus size (or both) caused the reversal of the GPE in Martin's experiment.

It has also been demonstrated that the location of the stimulus in the visual field can affect the strength and direction of precedence effects. Most of those experiments which have found a GPE have used peripheral stimulus presentation (eg., Navon, 1977, 1981b, 1983). Martin (1979) presented her stimuli randomly in one of four quadrants around a central fixation point. However, the presentation was not entirely peripheral because one corner of the compound letter always abutted the central fixation point, putting at least part of the stimulus in central vision.

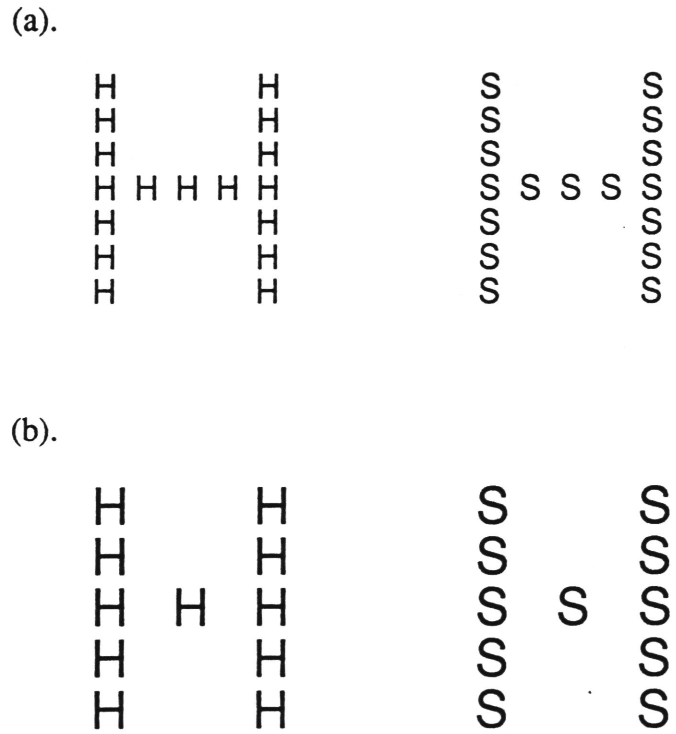


Figure 2. Compound letter stimuli similar to those used by Martin (1979). Densely-configured stimuli are shown at (a), and sparsely-configured stimuli are shown at (b). (Not to scale.)

Experiments which use centrally-presented (or close to centrally-presented) stimuli have often found no GPE, or even an apparent local precedence effect (eg., Hoffman, 1980, Kinchla & Wolfe, 1979; Lamb & Robertson, 1988). In some cases, a GPE occurred with central presentation, but a bi-directional inconsistency effect was found, in which the response times to both global and local letters were slowed by the presence of an inconsistent letter at the irrelevant level (eg., Luna, Merino & Marcos-Ruiz, 1990). Grice, Canham and Boroughs (1983) compared the effects of presenting compound stimuli in the centre and the periphery of the visual field. They found that only peripheral presentation produced a GPE and an inconsistency effect for the local letters. There was no significant GPE with central presentation, but there was a bi-directional inconsistency effect for both global and local letters. In a similar experiment, Pomerantz (1983) also found that a strong GPE occurred with peripheral presentation only. These researchers have generally argued that peripheral presentation makes the local elements less visible because of the lack of acuity in peripheral vision.

However, it could similarly be argued that central presentation makes the local elements more visible than the global elements. With most of the stimulus configurations used in the above experiments (such as the letters E, H and S) at least some of the local elements would appear at, or very close to, the central fixation point. This means that those local letters will fall in the high-acuity foveal area of the visual field. The global letters, on the other hand, are likely to fall at least partly in the periphery. It has already been noted above that Kinchla and Wolfe (1979) found that the GPE diminished in strength and eventually reversed into a local precedence effect as they increased the size of their centrally presented compound letter stimuli. The GPE disappeared when the compound letter was greater than about 7^{o} of visual angle. At this point, the boundaries of the global letter would have been more than 3.5^{o} from the central fixation point, and therefore encroaching on the less acutely perceived peripheral region of the visual field.

Navon and Norman (1983) have addressed this problem by using compound stimuli made of C and O shapes, with the fixation point in the centre of the C or O. The global and the local elements of such stimuli have equal eccentricity from the central fixation point. They used this configuration in sizes of 2^{o} of visual angle (all-foveal presentation) and 17.25^{o} (all-peripheral presentation). Under both size conditions, the local and global elements of the stimulus should have been equally visible since they both fell in the same region of the visual field. Navon and Norman found that both stimulus size conditions produced a significant GPE.

It is clear from these results that experimenters must ensure that, as far as possible, both the global and local elements of the stimulus fall within the same region of the visual field, or at least that they are equally visible. This is perhaps best done by presenting the entire stimulus at unpredictable locations around a central fixation point, in the periphery of the visual field. The stimulus might also be presented entirely in central vision, but in this case the compound letter would have to be quite small and there would be a danger that the local elements would be too small to be clearly visible.

1.5 Aims of the present experiments.

The general approach adopted in the experiments to be reported here has been to investigate the effect of a number of variables on the GPE. If the processes that contribute to the global precedence effect are the same as the low-level visual processes revealed in the studies outlined above, then the global precedence effect should be influenced by manipulations that are known to influence these psychophysical phenomena. If these variables have similar effects on the GPE to those they have on the perception of gratings, it can be argued that the GPE reflects the involvement of spatial frequency channels.

Consequently, the series of experiments to be reported here are designed to investigate the following questions:

(i) Martin's finding (1979) that the GPE was not inevitable but depended on (amongst other things) stimulus sparsity. Experiments 1(a) and 1(b) are an attempt to repeat Martin's experiment using consistently sized stimuli and more appropriate peripheral presentation positions for the stimuli.

(ii) Whether the GPE occurs in the absence of a concomitant inconsistency effect. Experiment 1(b) addresses this question through the use of neutral symbols (rectangles) instead of letters in the non-target level of the compound figure stimulus, so that the non-target level is never "consistent" or "inconsistent" with the target level letter.

(iii) The extent to which the GPE is present when local and global elements are equally visible. Experiment 2 addresses this question by using compound letter stimuli with equally visible global- and local-level letters.

(iv) The effect of colour on the GPE. Recent evidence suggests that the transient and sustained sub-systems are differentially affected by colour (Breitmeyer & Williams, 1990; Williams, Breitmeyer, Lovegrove & Gutierrez, 1991). Experiment 3 therefore investigates the effect of red, green and blue compound letter stimuli on the GPE.

(v) The effects of colour and spatial frequency adaptation on the GPE. Experiment 4 directly addresses the role of spatial frequency channels in the GPE by having the experimental subjects adapt to a coloured grating before they are presented with the compound letter stimuli, to see if this has any effect on the GPE.

CHAPTER 2.

2. EXPERIMENT 1(a).

2.1 The effect of stimulus density on the GPE.

Experiment 1(a) is intended to repeat Martin's experiment (1979) with the sizes of the global and local elements of the stimuli held constant for both densely and sparsely configured stimulus conditions, and with non-central stimulus presentation.

2.1.1 METHOD.

Subjects.

The subjects were 14 undergraduate psychology students who volunteered to participate in this experiment. All had normal or corrected-to-normal vision, and were aged from 18 to 53 years.

Apparatus and stimuli.

In the first of these experiments the influence of stimulus size was controlled by using compound letter stimuli in which the global letters and the local letters always remained the same size. At a viewing distance of 80 cm, the global letters measured $4.4^{o} \times 2.8^{o}$ of visual angle for all conditions, and the local letters were $0.3^{o} \times 0.2^{o}$. For the dense stimulus configuration the local letters were arranged in a 9 x 7 letter matrix, while for the sparse stimulus configuration they were arranged in a 5 x 4 letter matrix. This means that, unlike the stimuli used by Martin, there were wider gaps between the local letters in the sparse condition (Figure 3).

(a).

(b).

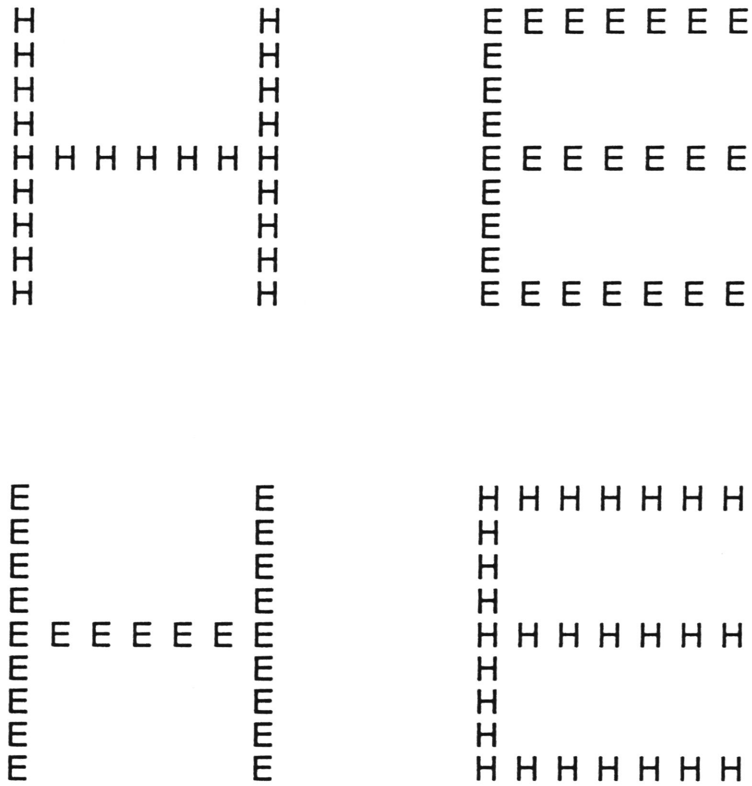


Figure 3. The set of compound letter stimuli used in Experiment 1(a), and subsequent experiments. Densely-configured consistent stimuli are shown at (a); densely-configured inconsistent stimuli are shown at (b). (Not to scale.) *Continued overleaf...*

(c).

```
H           H       E   E   E   E
H           H       E
H   H   H   H       E   E   E   E
H           H       E
H           H       E   E   E   E
```

(d).

```
E           E       H   H   H   H
E           E       H
E   E   E   E       H   H   H   H
E           E       H
E           E       H   H   H   H
```

Figure 3. *(Continued.)* The set of compound letter stimuli used in Experiment 1(a), and subsequent experiments. Sparsely-configured consistent stimuli are shown at (c); sparsely-configured inconsistent stimuli are shown at (d). (Not to scale.)

The stimuli were generated by a computer programme using the Micro Experimental Laboratories package (Schneider, 1988) run on an AH brand AT personal computer, and were displayed on the computer's 32 cm size President VGA colour VDU screen. The stimuli appeared as white letters on a black background. The luminances of the stimuli and background were measured using a Tektronix J6523 1^{o} narrow angle luminance probe. The letters had an average luminance of 30 cd/m^2 and the background had a luminance 0.3 cd/m^2. The contrast between stimulus and background was therefore 0.98.

Each compound letter was presented randomly to the left or right of the screen in each trial, so that the centre of the compound letter was 2.1^{o} of visual angle from a fixation point in the middle of the screen. This was intended to prevent subjects from performing the task by fixating on a particular local feature of the stimulus in a predictable area of the screen.

The left and right cursor keys of the computer's keyboard were re-labelled "E" and "H". These keys were used by the subjects to register their responses to target stimuli.

Procedure.

The experimental session began with 32 practice trials, followed by 160 test trials. The test trials were arranged in 4 randomly presented blocks of trials:

(i) Global-level target & dense configuration.

(ii) Global-level target & sparse configuration.

(iii) Local-level target & dense configuration.

(iv) Local-level target & sparse configuration.

In each block of trials the subject was asked to attend selectively to either the "large" (global-level target) or the "small" (local-level target) letters, and to identify the relevant letter as either "E" or "H" by pressing one of the two labelled keys.

Each of these blocks contained 40 randomly presented trials featuring equal numbers of consistent and inconsistent compound letters, and an equal frequency of left and right screen presentations.

Each trial consisted of the 3000 msec display of a small cross-shaped fixation point in the centre of the VDU screen, immediately followed by a compound letter stimulus to the left or right of this point. The stimulus remained in view until the subject made a response by pressing one of the keys. The computer then recorded both the response time (RT) and the accuracy of each response. RT was measured from the onset of the compound letter stimulus. The subjects were strongly encouraged to respond as quickly as possible without compromising accuracy. (The computer sounded a brief tone if the subject made a incorrect response.)

When the subject had responded, the compound letter was replaced by the display of a 1000 msec visual random noise mask, consisting of 0.3^{o}-long right- or left-leaning diagonal line segments placed at random over the entire screen area. The purpose of this display was to mask any lingering afterimage of the stimulus figure, either on the display screen or in the subject's visual system, in preparation for the presentation of the next stimulus display. (In Experiment 2, which used brief limited-duration displays, the mask also served to prevent the unintentional extension of the stimulus duration due to afterimages.)

The viewing distance was 80cm from the screen.

2.1.2 RESULTS.

The median RT for correct responses for each condition was calculated for each subject. The means and standard deviations of these RTs for all subjects are shown in Table 2. These results show the standard pattern of the GPE in both the dense and the sparse stimulus conditions, although the GPE is not as strong in the sparse conditions (Figure 4). Both the dense and the sparse conditions also produced an inconsistency effect, with a substantial increase in RT for local letters when the global letter was inconsistent with them (Figure 5).

These results were confirmed by submitting the RTs to a three-way analysis of variance.

Table 2.

Results of Experiment 1(a): Means and Standard Deviations (in msec.).

		Dense		Sparse	
		Consistent	Inconsistent	Consistent	Inconsistent
Global	mean	564.9	565.8	585.0	593.0
	sd	*111.0*	*105.6*	*117.6*	*126.8*
Local	mean	653.2	727.5	624.3	704.7
	sd	*117.8*	*85.0*	*91.3*	*116.1*

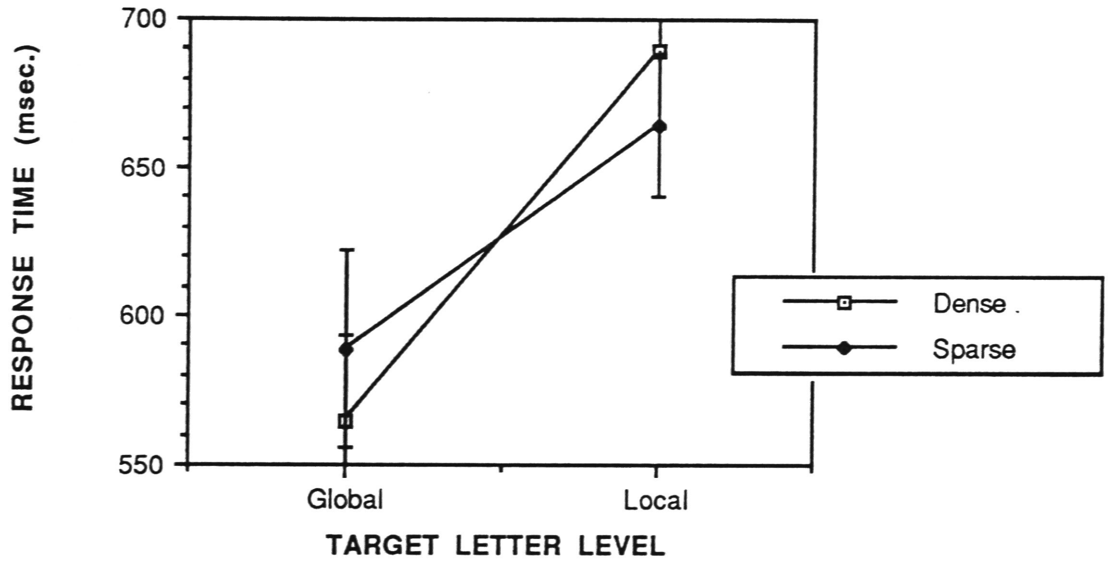


Figure 4. The global precedence results for Experiment 1(a). RTs (in msec.) are shown as a function of target letter level and stimulus density.

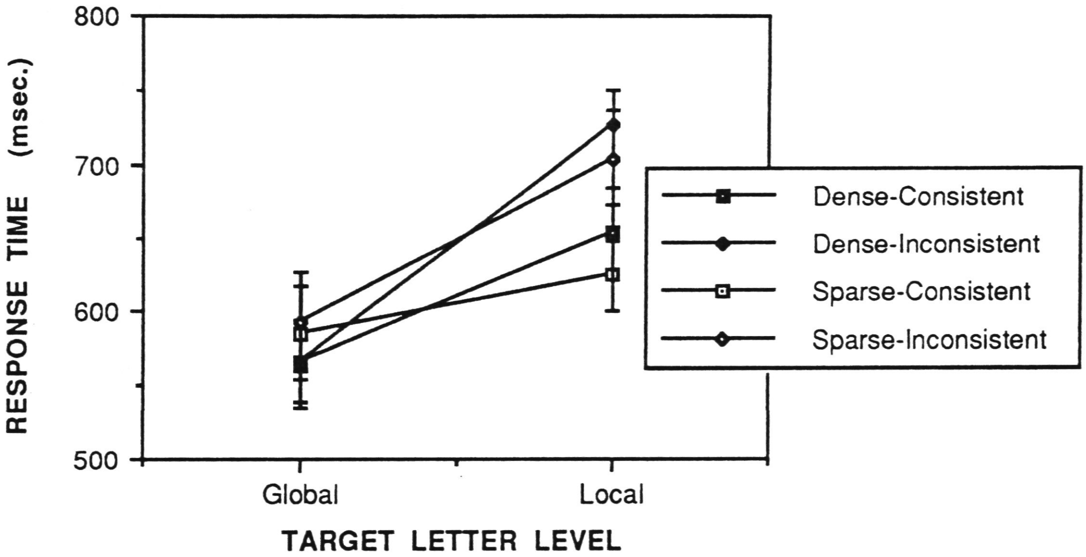


Figure 5. The inconsistency effect results for Experiment 1(a). RTs (in msec.) are shown as a function of target letter level, stimulus density, and letter consistency.

Global precedence effect.

The main effect for target letter level showed that the global letters were generally responded to significantly faster than the local letters [$F(1,13) = 27.22, p < .01$]. There was no significant main effect for stimulus density [$F(1,13) = 0.01, p > .10$], but there was a significant interaction between letter level and stimulus density [$F(1,13) = 8.45, p < .05$]. The latter result reflects the weaker GPE for the sparse stimulus configuration. Nevertheless, the GPE in the sparse stimulus conditions was still significant, (simple main effect of target letter level with sparse stimulus configuration [$F(1,18) = 12.91, p < .01$]).

Inconsistency effect.

The main effect for letter consistency showed that consistent letters were generally more quickly responded to than inconsistent letters [$F(1,13) = 15.99, p < .01$]; and there was a significant interaction between target letter level and letter consistency [$F(1,13) = 48.32, p < .0001$], reflecting an apparent inconsistency effect. This interaction was further investigated by looking at the simple main effects of letter consistency at each target letter level. The analysis revealed that there was no difference in RT to consistent and inconsistent letter stimuli when the global-level letter was the target, (simple main effect, [$F(1,19) = 0.15, p > .05$]); but there was a significant difference when the local-level letter was the target (simple main effect, [$F(1,19) = 45.25, p < .01$]). This is the standard inconsistency effect. There were no other significant interactions, indicating that stimulus density had no effect on the IE, (stimulus density x letter consistency interaction [$F(1,13) = 0.45, p > .10$]; letter level x stimulus density x letter consistency interaction [$F(1,13) = 0.01, p > .10$]).

Accuracy.

All subjects achieved a high degree of accuracy in their responses, with an average accuracy score of 98% (standard deviation = 3%). Since accuracy was always at or close to ceiling level no further analysis of accuracy scores was carried out.

2.2 DISCUSSION.

It now seems clear that both densely and sparsely configured stimuli will produce a GPE (and a IE) when the size of the global and local elements are held constant, and where one target level is not favoured by the presentation position.

It seems likely that Martin's finding (1979) of an apparent local precedence effect for sparsely-configured stimuli can be attributed to her use of relatively large local-level letters in her "sparse" stimuli, and perhaps also to the positioning of the stimuli so that some of the local-level letters always fell close to the centre of the visual field.

CHAPTER 3.

3. EXPERIMENT 1(b).

3.1 The effect of stimulus density on the GPE in the absence of an inconsistency effect.

Experiment 1(b) investigated whether the GPE would be affected by the absence of either consistent or inconsistent letters, by using a neutral figure (a rectangle) in the non-target level of the compound stimulus.

3.1.1 METHOD.

Subjects.

This experiment used 13 subjects, all of whom had participated in Experiment 1(a). All had normal or corrected-to-normal vision, and were aged from 18 to 53 years.

Apparatus and stimuli.

The apparatus was the same as that used in Experiment 1(a). The stimuli were modified versions of those used in Experiment 1(a). In this experiment the figure in the non-target level of the compound stimulus was always a neutral rectangle rather than a letter. When the local level of the stimulus was the target, the global figure was a large rectangle (4.4^{o} x 2.8^{o} of visual angle) composed of small letters E or H (0.3^{o} x 0.2^{o}) arranged in a 9 x 7 matrix for the dense configuration, or in a 5 x 7 matrix for the sparse configuration. When the global level of the stimulus was the target, the global figure was a large letter E or H (4.4^{o} x 2.8^{o} of visual angle) composed of small solid

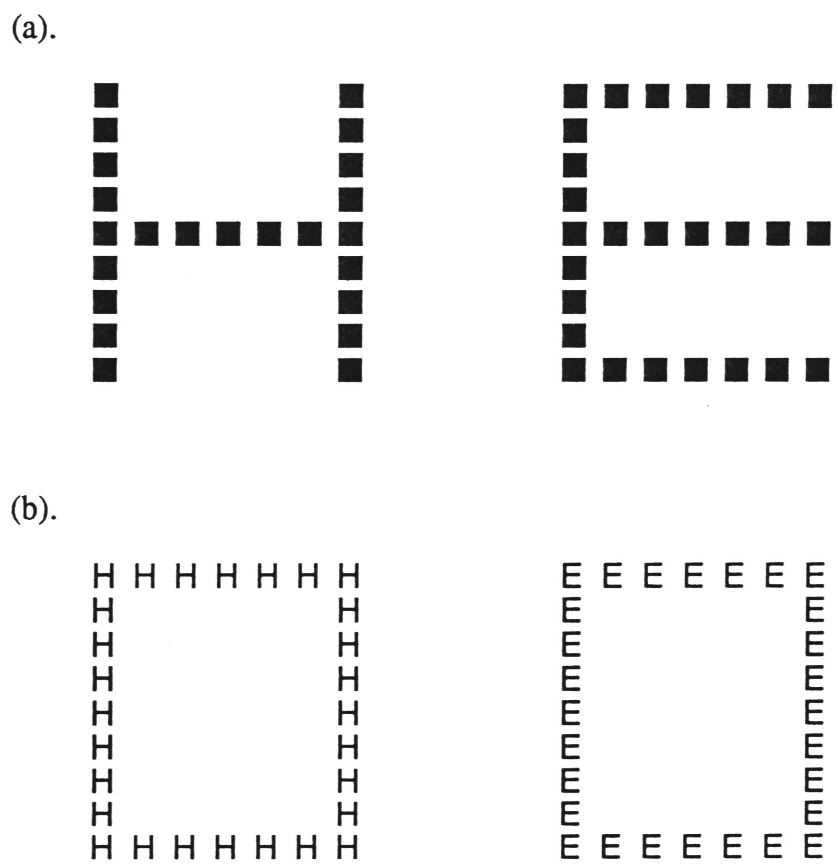
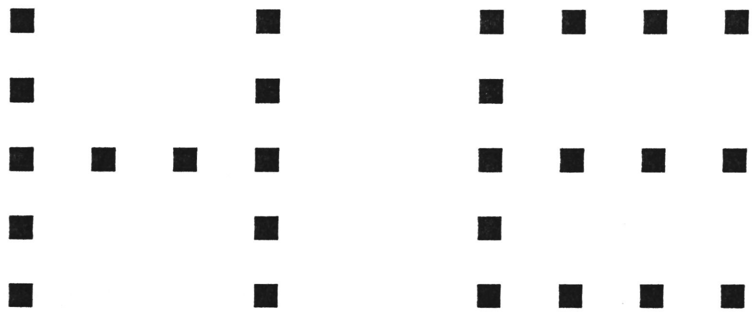


Figure 6. The set of compound letter stimuli used in Experiment 1(b). Densely-configured global-level target stimuli with neutral local elements are shown at (a); densely-configured local-level target stimuli with neutral global elements are shown at (b). (Not to scale.) *Continued overleaf...*

(c).



(d).

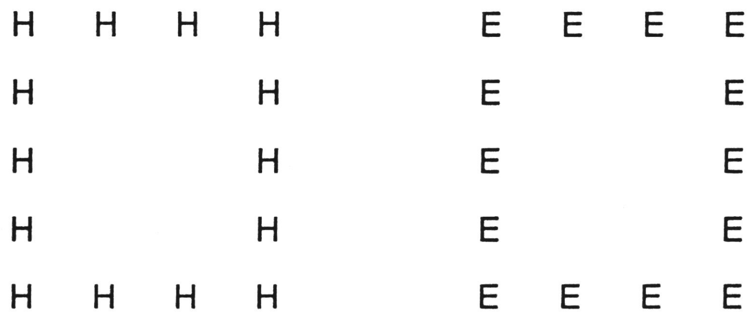


Figure 6. *(Continued.)* The set of compound letter stimuli used in Experiment 1(b). Sparsely-configured global-level target stimuli with neutral local elements are shown at (c); sparsely-configured local-level target stimuli with neutral global elements are shown at (d). (Not to scale.)

rectangles (0.25^{o} x 0.18^{o}) and arranged as above (Figure 6).

The letters had a luminance of 30 cd/m^2 and the background had a luminance 0.3 cd/m^2. The contrast between stimulus and background was therefore 0.98.

Procedure.

The procedure was similar to that used in Experiment 1(a). The only difference was the smaller number of trials per block (20 trials) due to the absence of a consistent/inconsistent letter variable. The total number of test trials was 80.

3.1.2 RESULTS.

The median RT for correct responses for each condition was calculated for each subject. The means and standard deviations of these RT scores are shown in Table 3. As in Experiment 1(a), the results for Experiment 1(b) show a standard GPE for both dense and sparse stimulus configurations, with a weaker GPE for the sparse conditions (Figure 7).

These results were confirmed by submitting the RTs to a two-way analysis of variance.

Global precedence effect.

The main effect for target letter level showed that the global letter targets were responded to significantly faster than the local letter targets [$F(1,12) = 65.31, p < .0001$]. There was no significant main effect for stimulus density [$F(1,12) = 0.12, p > .10$]. However, there was a significant interaction between target letter level and stimulus density [$F(1,12) = 6.06, p < .05$], reflecting the weaker GPE for the sparse stimulus configuration. Although relatively weak, this GPE was still significant, (simple main effect of target letter level for sparse stimuli, [$F(1,23) = 21.53$, $p < .01$]).

Accuracy.

All subjects achieved a high degree of accuracy in their responses, with an average accuracy score of 98% (standard deviation = 3%).

Table 3.

Results of Experiment 1(b): Means and Standard Deviations (in msec.).

		Dense	Sparse
Global	mean	525.1	551.4
	sd	*115.8*	*107.3*
Local	mean	641.2	620.6
	sd	*96.9*	*130.7*

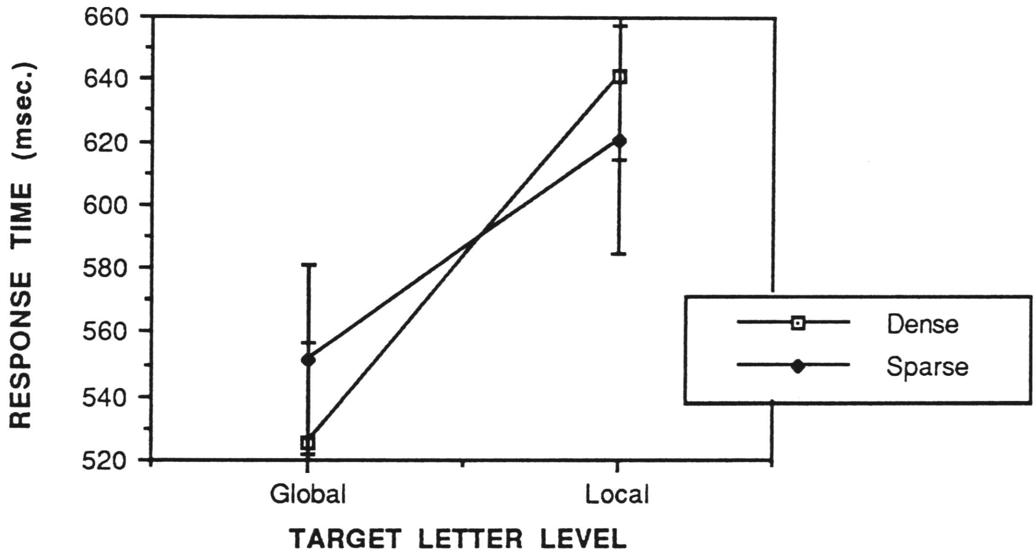


Figure 7. The global precedence results for Experiment 1(b). RTs (in msec.) are shown as a function of target letter level and stimulus density.

3.2 DISCUSSION.

The close similarity of the results of Experiments 1(a) and 1(b) indicates that the GPE does not rely on the presence of an IE, so the two effects are not necessarily connected or produced by the same cognitive processes.

The results of Experiments 1(a) and 1(b) contradict Martin's (1979) finding of an apparent local precedence effect with a sparse stimulus configuration, but it leaves us with the question of why the GPE was weaker in the sparse stimulus conditions. The sizes of the global and local letters were held constant, so size changes could not account for changes in the strength of the GPE in this case.

One possible explanation could be a difference in relative visibility between the global and local letters. In the dense stimulus configuration, the local letters were very close to each other in space and so may be less visible due to lateral inhibition in the visual system (Podrouzek, Modigliani, & Di Lollo, 1992). As we have seen, lateral inhibition caused by similar stimuli presented close together in space may occur at the retinal, LGN or cortical levels (Hubel & Wiesel, 1962, 1965, 1968; Kuffler, 1953, Maffei & Fiorentini, 1972). Conversely, the greater distance between local letters in the sparse condition may prevent lateral inhibition from coming into play, leaving the local letters more visible.

At the same time, the sparsity of the local elements in the sparse configuration is likely to make the global letter less visible because of a lack of continuity of contour. Hoffman (1980) found that if he distorted the shape of the global letter in a compound letter stimulus by having one of the local letters set out of alignment with the rest, subjects would display a local precedence effect, presumably because the global letter was now relatively less visible. (He argued that the GPE may be produced by the standard compound letter stimulus because the local letters here are somehow less visible than the global letter, and the better quality information about the global letter allows faster recognition.)

Using compound geometric shapes, Navon (1983) found that the GPE could be weakened if the local elements were arranged in such a way that the "edges" of the global shape were not smooth. He also found that the GPE could be more difficult to produce if the global figure was made up of only a small number of local elements, regardless of the density of the configuration. Boer and Keuss (1982) found that the GPE was lost if a few of the local letters in a compound stimulus were presented at a higher luminance than the rest. Presumably this made the local letters relatively more visible, and perhaps also interfered with the perception of the global letter because of the unevenness of luminance across the global figure.

To investigate the role of relative visibility in the GPE a second experiment was carried out which attempted to make the visibility of the stimulus components equal.

CHAPTER 4.

4. EXPERIMENT 2.

4.1 The effect of stimulus density on the GPE when global and local elements are equally visible.

Experiment 2 investigated whether the GPE found in Experiment 1(a) would still occur if all stimulus conditions were made equally visible. This was done by manipulating the display duration for each type of stimulus until the subject attained an equivalent degree of accuracy for each stimulus type.

4.1.1 METHOD.

Subjects.

Subjects were drawn from the same population as those in Experiment 1. Twelve subjects were initially tested, but 4 were excluded from the final analysis because they failed to achieve the 80% accuracy criterion. The results shown below represent the remaining 8 subjects.

Stimuli.

The stimuli were the same as those used in Experiment 1(a) (Figure 3).

Procedure.

The procedure was similar to that used in Experiment 1(a). However, in order to limit the visibility of the stimulus, the compound letter was displayed for brief set durations of 10, 40, 70 or 100 msecs, and followed immediately by a 1000 msec random noise mask. Response time was measured from the onset of the letter stimulus.

Each subject was pre-tested for all stimulus conditions with all four durations. Thirty practice trials were followed by 448 test trials (14 trials for each condition). From these results it was possible to determine, for each stimulus condition, the minimum duration which allowed the subject to achieve at least 80% accuracy in their responses. (See Appendix F.)

Each subject was then re-tested, with each stimulus type displayed for the optimal duration determined in the pre-test stage for that particular subject. This should have ensured that all stimulus types - global and local, dense and sparse, consistent and inconsistent - were equally visible to the subject.

4.1.2 RESULTS.

RTs were determined for each subject as in Experiment 1(a), and the mean RTs and standard deviations for each condition are shown in Table 4.

The data were submitted to a three-way analysis of variance.

Global precedence effect.

The GPE results are shown in Figure 8. Despite the fact that all stimulus types should now be equally visible a significant GPE was found, with the global letters being responded to more quickly than the local letters, (main effect for target letter level, [$F(1,7) = 7.93$, $p < .05$].) Once again there was no overall difference in RT between the dense and the sparse stimuli, (main effect for stimulus configuration, [$F(1,7) = 0.08$, $p > .10$]), although the weaker GPE for the sparse configurations was reflected in a significant interaction between target letter level and letter density [$F(1,7) = 55.76$, $p < .0001$]. Although the results for the sparse stimuli suggest a standard GPE, the effect is not significant this time, (simple main effect of target letter level with sparse stimuli, [$F(1,7) = 3.57$, $p > .05$]). The failure to achieve statistical significance in this case may be due to the relatively small sample size in this experiment. On the basis of the overall results, however, it seems unlikely that the GPE can be attributed solely to differences in relative visibility.

Inconsistency effect.

The IE results are shown in Figure 9. Although the results of this experiment show a pattern suggesting an inconsistency effect, it was not statistically significant, (main effect for letter consistency, [$F(1,7) = 1.64$, $p > .10$]; letter level x letter consistency interaction, [$F(1,7) = 3.05$, $p > .10$]). There were no other significant interactions.

Accuracy.

Mean accuracy was 93%, (standard deviation = 8%).

Table 4.

Results of Experiment 2: Means and Standard Deviations (in msec.).

		Dense		Sparse	
		Consistent	Inconsistent	Consistent	Inconsistent
Global	mean	490.6	482.7	542.3	552.6
	sd	*80.2*	*78.2*	*95.2*	*63.5*
Local	mean	703.3	744.2	661.3	675.5
	sd	*234.4*	*238.4*	*258.8*	*221.0*

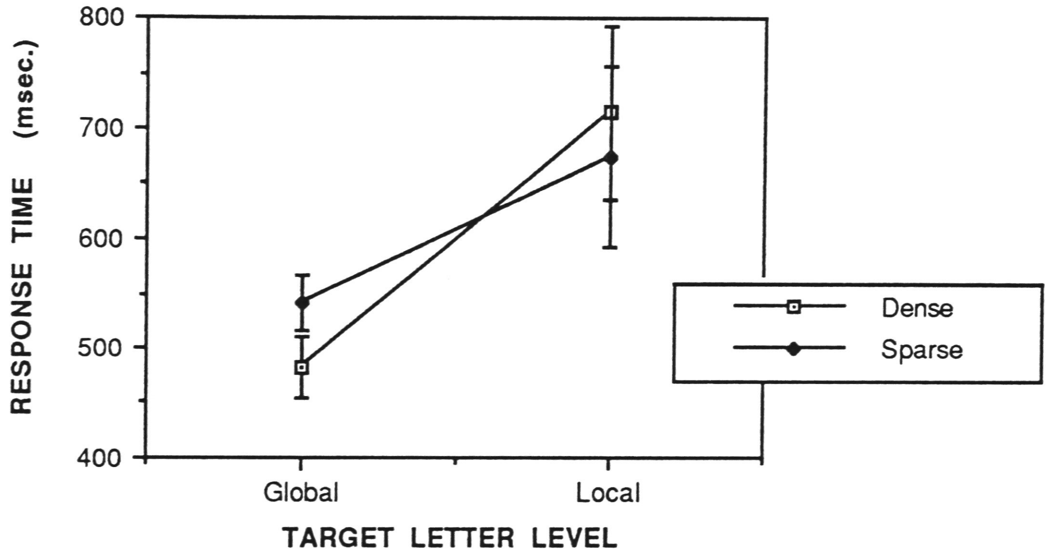


Figure 8. The global precedence results for Experiment 2. RTs (in msec.) are shown as a function of target letter level and stimulus density.

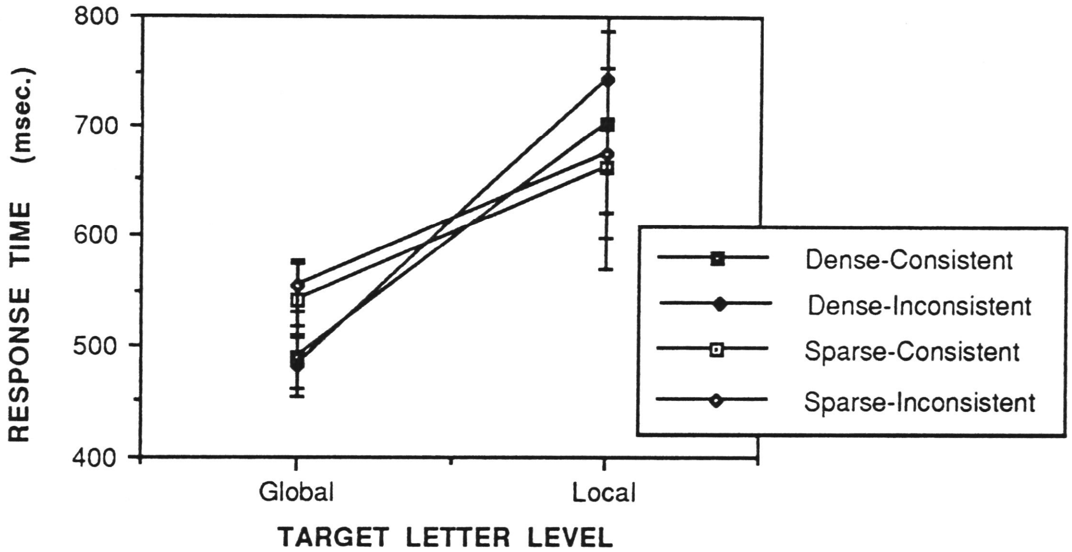


Figure 9. The inconsistency effect results for Experiment 2. RTs (in msec.) are shown as a function of target letter level, letter consistency and stimulus density.

4.2 DISCUSSION.

Our results generally corroborate the findings of Hughes, Layton, Baird and Lester (1984). In an experiment using equally visible horizontal and vertical compound line segments made up of small line segments, they found standard GPE and inconsistency effects. Interestingly, these researchers also discovered that the strength of the GPE decreased as luminance increased. Previous studies which found little or no GPE had often used high luminance stimuli (eg., Kinchla & Wolfe, 1979; Pomerantz, 1983), so the luminance level may have played a part in producing the reversals in the GPE in such cases.

The combined data from the experiments reported above demonstrate the general robustness of the global precedence effect, while also demonstrating that it may be influenced by retinal size, stimulus density and position, but only marginally by relative visibility. As these results are predictable from our knowledge of low-level visual processes they lend support to the theory that the GPE arises from the operation of low-level visual processes such as spatial frequency channels.

CHAPTER 5.

5. EXPERIMENT 3.

5.1 The effect of colour on the GPE.

There is some evidence that the perception of colour is connected with the transient and sustained visual sub-systems. In general, the parvo (sustained) pathway is sensitive to colour while the magno (transient) pathway is effectively "colour-blind" (Livingstone & Hubel, 1988). However, while the transient sub-system may not be able to identify colours, there is evidence that the functioning of this sub-system may be inhibited or enhanced by lights of different wavelengths. It has been established that long-wavelength (red) stimuli can inhibit activity of the magno/transient pathway (Breitmeyer & Williams, 1990, with humans; Dreher, Fukuda & Rodieck, 1976; Schiller & Malpeli, 1978, with monkeys). Using a metacontrast masking paradigm, Williams, Breitmeyer, Lovegrove and Gutierrez (1991, with humans) concluded that long-wavelength (red) stimuli inhibit activity in the transient sub-system, short-wavelength (blue) stimuli enhance activity in the transient sub-system, and medium-wavelength (green) stimuli have a relatively neutral effect.

If low-level visual processes underlie the GPE, it is therefore likely that the use of different coloured stimuli will have a differential effect on the GPE. Specifically, the hypothesis predicts that the use of a blue stimulus should favour the perception of low spatial frequency aspects of the stimulus (such as the global letter in a compound letter) relative to the high frequency aspects of the stimulus (such as the local letter), because blue light enhances transient activity. Red stimuli, on the other hand, should favour the perception of high frequency stimuli at the expense of the low frequency stimuli, because red light inhibits transient activity. In short, a blue stimulus should produce a stronger GPE than a red stimulus. Experiment 3 investigated this possibility.

5.1.1 METHOD.

Subjects.

14 subjects were drawn from the same population as that used in Experiment 1. (Age range: 18-42 years).

Apparatus and stimuli.

The apparatus was the same as that used in Experiment 1.

This experiment used only the set of dense compound letter stimuli from Experiment 1 (Figure 3). However, in this experiment each compound letter stimulus was one of three colours: red (long wavelength), green (medium wavelength), or blue (short wavelength).

The luminances of the three colours were matched at 15.8 cd/m^2. The luminances of the three colours were set at equal levels using the colour palette setting mechanism of the MEL package. This allowed patches of each colour to be displayed on the computer's VDU screen. Each colour patch was as pure in hue as possible. For the red patch only the red pixels of the VDU were turned on, for the green patch only the green pixels were turned on, and for the blue patch only the blue pixels were turned on. Each colour patch could be displayed at one of 64 luminances. The luminance of each colour patch was varied until all three were of the same luminance (15.8 cd/m^2), as measured by a Tektronix J6523 1° narrow angle luminance probe. The computer programme which displayed the compound letter stimuli in the experiment was then modified so that it displayed the three colours at these luminance settings.

The luminance of black background was 0.2 cd/m^2, producing a contrast of 0.98.

Procedure.

The procedure was generally the same as that used in Experiment 1. The experimental session began with 24 practice trials followed by 240 test trials (20 trials for each condition). The test trials were arranged in 4 randomly presented blocks of trials:

(i) Global level target (twice).

(ii) Local level target (twice).

In each block of trials the subject was asked to attend selectively to either the "large" (global-level target) or the "small" (local-level target) letters, and to identify the relevant letter as either "E" or "H" by pressing one of the two labelled keys.

Each of these blocks contained 60 randomly presented trials featuring equal numbers of consistent and inconsistent compound letters, an equal frequency of left and right screen presentations, and an equal number of each of the three colour conditions.

Each trial consisted of the 3000 msec display of a small white fixation point in the centre of the VDU screen immediately followed by a coloured compound letter stimulus to the left or right of this point. The stimulus remained in view until the subject made a response by pressing one of the keys. The computer then recorded both the reaction time (RT) and the accuracy of each response. RT was measured from the onset of the compound letter stimulus. The subjects were strongly encouraged to respond as quickly as possible without compromising accuracy. (The computer sounded a brief tone if the subject made a incorrect response.) When the subject had responded, the compound letter was replaced by a 1000 msec visual random noise mask of the same colour.

5.1.2 RESULTS.

RTs were determined for each subject as in Experiment 1(a), and the mean RTs and standard deviations are shown in Table 5. The results would seem to indicate that blue stimuli produce a stronger GPE than red or green stimuli (Figure 10). This pattern of results is consistent with the hypothesis that faster perception of the global letter is mediated by the fast-transmitting transient visual sub-system. All colour conditions appear to produce an IE (Figure 11).

The data were submitted to a three-way analysis of variance. A comparison of the obtained *F* ratios with the Geisser-Greenhouse corrected critical *F* value, $F(1,13) = 4.67$, showed that all but one significant obtained *F* exceeded this value. Any violation of the assumption of sphericity would have no effect on the interpretation of these obtained *F* ratios, so it was not necessary to apply any adjustment to these results. The only exception was the target letter level x colour interaction (see below). A test of sphericity was performed on the data set for this interaction. This test found that the assumption of sphericity was not violated (Mauchly test of sphericity, $W = 0.93$, $p > .10$), and the Huynh-Feldt epsilon was 1.0. It was therefore not necessary to adjust the results for this interaction (Keppel, 1991).

Table 5.

Results of Experiment 3: Means and Standard Deviations (in msec.).

		Red	
		Consistent	**Inconsistent**
Global	mean	549.6	547.2
	sd	*101.0*	*93.2*
Local	mean	639.4	705.0
	sd	*132.7*	*134.5*

		Green	
		Consistent	**Inconsistent**
Global	mean	546.8	550.5
	sd	*68.7*	*111.0*
Local	mean	631.8	696.2
	sd	*103.0*	*97.9*

		Blue	
		Consistent	**Inconsistent**
Global	mean	531.0	539.4
	sd	*63.1*	*86.6*
Local	mean	664.3	707.6
	sd	*128.5*	*91.8*

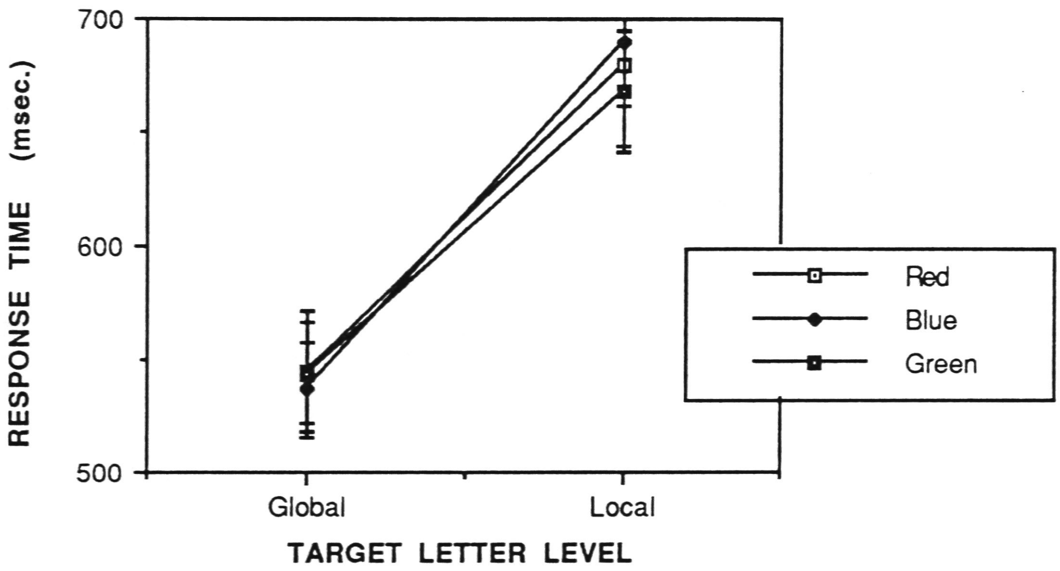


Figure 10. The global precedence results for Experiment 3. RTs (in msec.) are shown as a function of target letter level and stimulus colour.

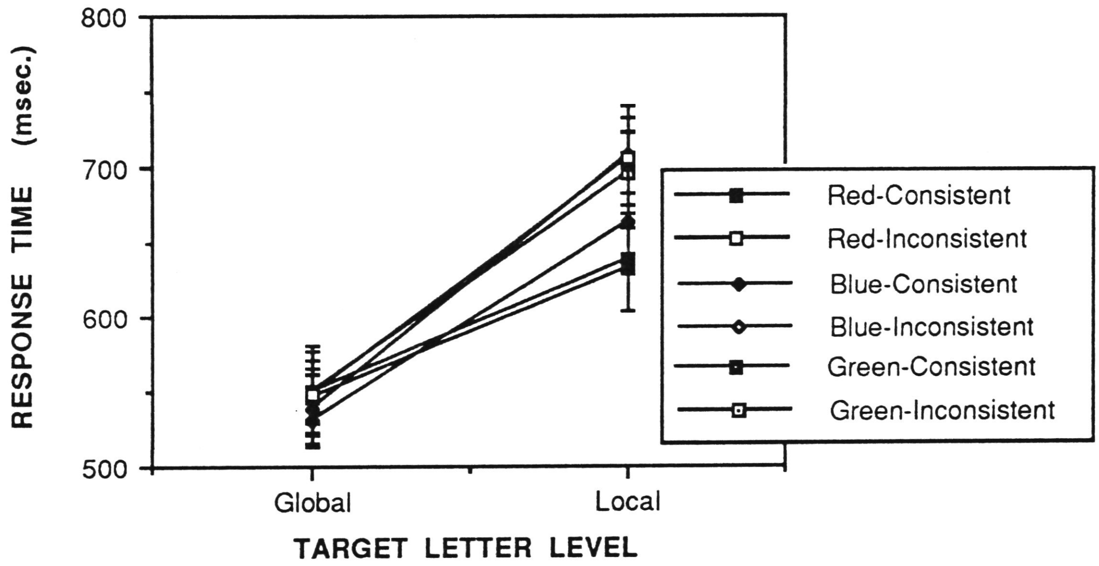


Figure 11. The inconsistency effect results for Experiment 3. RTs (in msec.) are shown as a function of target letter level, letter consistency and stimulus colour.

Global precedence effect.

The analysis of variance revealed a significant overall GPE, (main effect of letter level [$F(1,13) = 91.28, p < .001$]).

There was no significant main effect of colour [$F(2,26) = 0.26, p > .10$], so it was clear that no colour was more visible than the others on average. However, there was a significant interaction between colour and target letter level [$F(2,26) = 4.35, p < .05$], confirming that the different colours did differentially affect the strength of the GPE. The nature of this interaction was further explored using interaction contrasts (Keppel,1991). The interaction contrast of target letter level and colour (red and blue stimuli only) was significant [$F(1,13) = 5.31, p < .05$], showing that the GPE for the blue stimuli was stronger than that for the red stimuli, as predicted.

No predictions were made about the effect of green stimuli on the GPE because little is known about the effect of green light on the transient sub-system. The results of the present experiment suggest that green stimuli have an effect similar to that of red stimuli. The interaction contrast of target letter level and colour (red and green stimuli only) was not significant [$F(1,13) = 0.36, p > .05$], indicating that there was no difference in the strength of the GPE between red and green stimuli. Although they were relatively weak, the GPEs for the red and green stimuli were still significant, (simple main effect for target letter level with red stimuli [$F(1,21) = 64.49, p < .01$], simple main effect for target letter level with green stimuli [$F(1,21) = 56.02, p < .01$]).

Inconsistency effect.

There was a significant general inconsistency effect, (main effect of letter consistency [$F(1,13) = 66.2, p < .0001$]; interaction of letter level and letter consistency [$F(1,13) = 13.95, p < .01$]). There was no significant difference in RT between consistent and inconsistent letters when the target was the global level, (simple main effect of letter consistency for global level targets [$F(1,19) = 0.15, p > .05$]); but the RTs for the local level targets were significantly slower when the letters were inconsistent, (simple main effect of letter consistency for local level targets [$F(1,19) = 49.49, p < .01$]).

There was no significant interaction of colour with letter consistency [$F(2,26) = 0.21, p > .10$], or colour with letter level and letter consistency [$F(2,26) = 0.92$), $p > .10$], indicating that the inconsistency effect was not affected by colour.

Accuracy.

Once again the subjects responded with a high level of accuracy, (mean=98%; standard deviation=3%).

5.2 DISCUSSION.

The results of this experiment demonstrate that the strength of the GPE can be affected by stimulus wavelength (colour), thus confirming our predictions based on the known wavelength-specific characteristics of the transient sub-system. This is further evidence for the involvement of low-level mechanisms in the GPE. (This finding is especially significant given that only the stimulus letters were coloured. If the backgrounds had been coloured it is possible that the differential effects of the different colours would have been even stronger.)

The failure to find an effect of stimulus wavelength on the inconsistency effect suggests that this effect may reflect higher-order processes rather than low-level visual processes.

CHAPTER 6.

6. EXPERIMENT 4.

6.1 The effects of spatial frequency and colour adaptation on the GPE.

It has been demonstrated both physiologically and psychophysically that adaptation to gratings of a particular spatial frequency will selectively diminish the sensitivity of the visual system to other stimuli of the same and similar spatial frequencies for some time afterwards (eg., Blakemore & Campbell, 1969; Blakemore, Nachmias & Sutton, 1970; Graham & Nachmias, 1971; Maffei, Fiorentini & Bisti, 1973; Pantle & Sekuler, 1968). This is thought to occur because the visual spatial frequency channel corresponding to the spatial frequency of the adapting grating has become fatigued.

Similarly, adaptation to gratings of a particular colour are known to lower the visual system's sensitivity to stimuli of that colour and spatial frequency and enhance sensitivity to those of a similar spatial frequency but "opposite" colour (Lovegrove & Over, 1972; McCollough, 1965). There is considerable evidence that colour vision involves a system of opponent processes. In general, it seems that the perception of red and green is connected in an opponent fashion, as is the perception of blue and yellow. In addition to the psychophysical evidence already mentioned, DeValois and DeValois (1975) have found LGN parvo cells which have colour-specific on-off receptive fields. For example, such a cell may increase its activity when red light appears in its receptive field, but reduce its activity in the presence of green light, or vice versa. Other such cells display a blue-yellow opponency.

If the GPE is brought about by the operation of low level processes such as spatial frequency and colour channels, the GPE should be able to be modified by first adapting the subjects to spatial frequencies and colours similar to those which occur in the compound letter stimuli. Experiment 4 tested this hypothesis.

6.1.1 METHOD.

Subjects.

18 subjects were drawn from the same population used in the previous experiments. (Age range: 18-51 years.)

Apparatus and stimuli.

The apparatus and compound letter stimuli were the same as those used in Experiment 3, except that only the red and green stimuli were used. Both red and green stimuli had a luminance of 30 cd/m^2, and the black background was 0.3 cd/m^2. The contrast was thus 0.98.

Two types of adaptation stimuli were used, and like the compound letter stimuli they were generated by computer programme and displayed on the computer VDU screen. The first adaptation condition employed a red vertical square wave grating on a black background as the adaptation stimulus. The bars of the grating were approximately the same width as the local letters in the compound letter stimuli (0.18^{o} of visual angle), which is equivalent to a spatial frequency of 2.8 cycles/deg. Adaptation to a red grating is expected to inhibit the subsequent perception of red stimuli of similar spatial frequencies, but possibly enhance perception of green stimuli of similar spatial frequencies (Lovegrove & Over, 1972; McCollough, 1965). The red grating bars and black background had luminances of 30 cd/m^2 and 0.3 cd/m^2, respectively. The second adaptation condition was a control condition which employed a blank grey field with a luminance equal to the average luminance of red grating stimulus (14.8 cd/m^2).

The colours and luminances of the stimuli and gratings in this experiment were set using the same method described in Experiment 3.

Procedure.

The procedure was similar to that used in Experiment 3, apart from the inclusion in this experiment of adaptation stimuli prior to the presentation of the compound letter stimuli. The experiment was conducted in two separate sessions several days apart, because the effects of adaptation to gratings have been known to last for several days (McCollough, 1965; Riggs, White & Eimias, 1974). In one of these sessions, the subjects were asked to adapt to the red grating for 5 minutes before the test trials with the compound letter stimuli were run. In the other (control) session they were asked to adapt to the blank grey field only. The adaptation was refreshed by 1 minute re-presentations of the adaptation stimulus at approximately 4 minute intervals throughout the experiment. The order of presentation of these two adaptation conditions was randomised across subjects.

Each session began with 24 practice trials followed by 160 test trials (20 trials for each stimulus type). The test trials were arranged in 4 randomly presented blocks of trials:

(i) Global-level target (twice).

(ii) Local-level target (twice).

In each block of trials the subject was asked to attend selectively to either the "large" (global-level target) or the "small" (local-level target) letters, and to identify the relevant letter as either "E" or "H" by pressing one of the two labelled keys.

Each of these blocks contained 40 randomly presented trials featuring equal numbers of consistent and inconsistent compound letters, an equal frequency of left and right screen presentations, and an equal number of each of the two stimulus colour conditions.

Each trial consisted of the 3000 msec display of a small white fixation point in the centre of the VDU screen immediately followed by a coloured compound letter stimulus to the left or right of this point. The stimulus remained in view until the subject made a response by pressing one of the keys. The computer then recorded both the reaction time (RT) and the accuracy of each response. RT was measured from the onset of the compound letter stimulus. The subjects were strongly encouraged to respond as quickly as possible without compromising accuracy. (The computer sounded a brief tone if the subject made a incorrect response.) When the subject had responded, the compound letter was replaced by a 1000 msec visual random noise mask of the same colour.

6.1.2 RESULTS.

RTs were calculated for each subject as in the previous experiments, and the mean RTs and standard deviations are shown in Table 6.

The data were submitted to a four-way analysis of variance.

Global precedence effect.

The GPE results are shown in Figure 12. A 4-way analysis of variance indicated that a general GPE was present, (main effect of letter level [$F(1,17) = 145.86$, $p < .0001$]).

Adaptation to the grating seemed to produce generally slower response times than adaptation to the uniform field, (main effect of adaptation type [$F(1,17) = 4.83$, $p < .05$]). However, the significant interaction between target letter level and adaptation type [$F(1,17) = 6.65$, $p < .05$] confirmed that adaptation to the grating differentially affected RT to the global and local letters. Specifically, adaptation to the grating seemed to increase substantially the RT to the global letter while having little effect on responses to the local letters, thus weakening the GPE (simple main effect of adaptation type for global target letters, [$F(1,27) = 10.14$, $p < .01$]; simple main effect of adaptation type for local target letters, [$F(1,27) = 0.41$, $p > .05$].) The grating that was used here was relatively low-frequency (2.8 cyc/deg). Presumably, it is composed of spatial frequency components which are similar to those needed to identify the global letter in the compound stimulus. In order to distinguish between an H and an E, the subject needs information about the arrangement of the lines that make up the letter. The adapting grating in this experiment was the same width as the "lines" making up the global letters.

It seems that the red letter stimuli were on average responded to slightly faster than the green letters despite the fact that they were equal in luminance and contrast, (main effect of letter colour [$F(1,17) = 5.47$, $p < .05$]). However, adaptation to the colour red in the red grating seemed not to have any differential effect on perception of compound letters of either colour, (interaction of adaptation type x letter colour [$F(1,17) = 0.01$, $p > .10$], interaction of adaptation type x letter colour x letter level [$F(1,17) = 0.38$, $p > 0.10$]).

Inconsistency effect.

The IE results are shown in Figure 13. A general inconsistency effect was found, (main effect of letter consistency [$F(1,17) = 32.36$, $p < .0001$], interaction of letter level and letter consistency [$F(1,17) = 21.75$, $p < .01$]). This interaction was further analysed using tests of simple main effects. These confirmed that letter inconsistency increased RTs for local target letters, but had no effect on RTs to global target letters, (simple main effect of letter consistency on local target letters, [$F(1,34) = 53.29, p < .01$]; simple main effect of letter consistency on global target letters, [$F(1,34) = 0.25, p > .05$].)

Adaptation to the grating, however, seemed to cause no significant change in the inconsistency effect, (interaction of adaptation type x letter consistency [$F(1,17) = 2.55, p > .10$], interaction of adaptation type x letter level x letter consistency [$F(1,17) = 1.62, p > .10$], interaction of adaptation type x letter colour x letter consistency [$F(1,17) = 2.13, p > .10$], interaction of adaptation type x letter colour x letter level x letter consistency [$F(1,17) = 0.04, p > .10$]). No other interactions were significant.

Accuracy.

The subjects all maintained a high level of accuracy in their responses, with a mean accuracy of 99% and a standard deviation of 3%.

Table 6.

Results of Experiment 5: Means and Standard Deviations (in msec.).

		No Adaptation Grating			
		Red Letters		Green Letters	
		Consistent	Inconsistent	Consistent	Inconsistent
Global	mean	522.0	512.5	530.4	529.6
	sd	*70.8*	*80.0*	*86.7*	*91.0*
Local	mean	619.6	678.3	625.6	681.2
	sd	*94.3*	*90.1*	*87.3*	*81.3*

		With Adaptation Grating			
		Red Letters		Green Letters	
		Consistent	Inconsistent	Consistent	Inconsistent
Global	mean	566.3	583.8	586.9	595.5
	sd	*121.1*	*142.9*	*119.6*	*142.9*
Local	mean	627.1	699.8	640.1	685.8
	sd	*102.6*	*96.8*	*107.4*	*79.0*

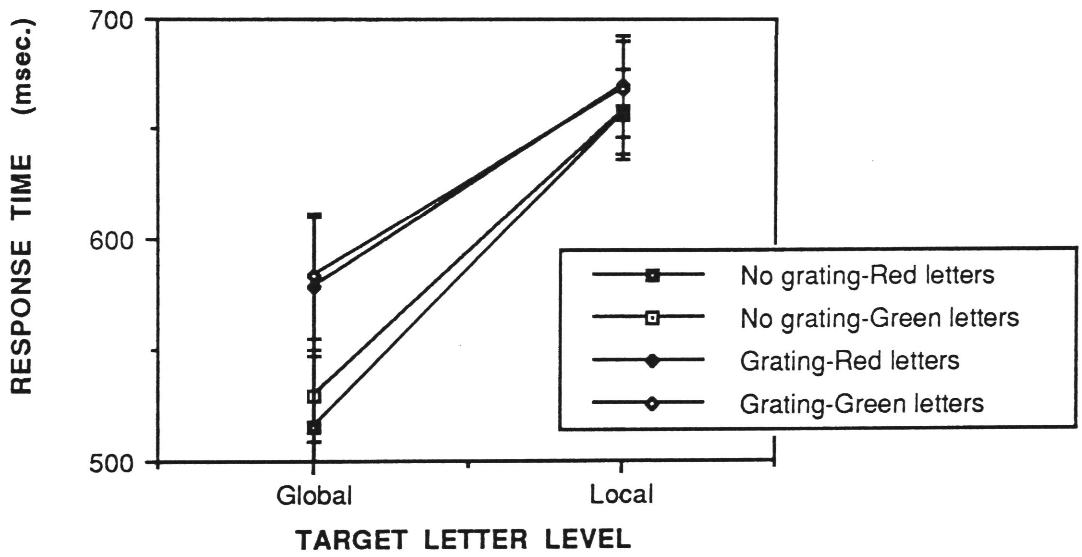


Figure 12. The global precedence results for Experiment 4. RTs are shown as a function of target letter level, adaptation type, and letter colour.

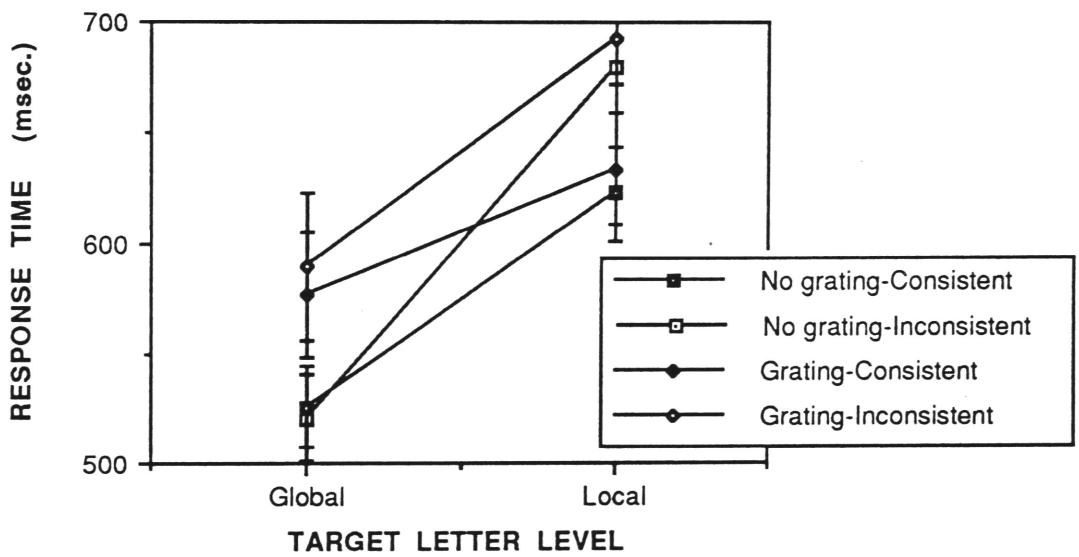


Figure 13. The inconsistency effect results for Experiment 4. RTs are shown as a function of target letter level, adaptation type, and letter consistency.

6.2 DISCUSSION.

These results corroborate the findings of a similar experiment by Shulman, Sullivan, Gish and Sakoda (1986). Using adaptation gratings of various spatial frequencies they found performance in global-target conditions was most affected by adaptation to low spatial frequencies, while performance in local-target conditions more affected by adaptation to high spatial frequencies. (This experiment did not use colour.) These demonstrations of the effect of spatial frequency adaptation of the GPE further implicates low-level mechanisms, because they show that the strength of the GPE can be affected by suppressing a particular spatial frequency channel through adaptation.

The absence of colour-specific adaptation effects in the present experiment may best be understood in terms of the spatial frequency content of the adaptation stimuli used. It has been shown previously (Lovegrove & Badcock, 1981) that colour selectivity in the tilt illusion (an illusion produced by adaptation to tilted gratings) is only found with high and not with low spatial frequency stimuli. This is consistent with the general finding that, at least in the early retinal and LGN stages, the magno (transient) pathway is sensitive to low frequencies but insensitive to colour (Livingstone & Hubel, 1988). The adaptation grating used in this experiment was relatively low frequency (2.8 cyc/deg).

The failure of grating adaptation to influence the inconsistency effect suggests that IE and the GPE probably reflect different mechanisms, and that the IE is not a product of low-level visual processes.

6.3 Related evidence on the role of spatial frequency channels in the GPE: The effects of uniform field flicker and spatial frequency filtering.

Adaptation to gratings is not the only way to manipulate the involvement of visual spatial frequency channels. The transient visual sub-system, which appears to mediate the perception of low spatial frequency stimuli, is also particularly sensitive to stimulus onset and offset, movement and flicker. It has been demonstrated that the use of a uniform field flicker (UFF) mask can increase response times, evoked potential latencies and contrast detection thresholds for low spatial frequency stimuli, but not for high spatial frequency stimuli (Baro & Lehmkuhle, 1989, 1990; Breitmeyer, Levi & Harwerth, 1981). If the GPE is produced by the role of the fast-transmitting transient system in perceiving the global aspect of the stimulus, then it should be possible to weaken or obliterate the GPE if we add a UFF mask to the compound stimulus.

In a study using compound letter stimuli, Lovegrove, Lehmkuhle, Baro and Garzia (1991) found that the addition of a 12Hz UFF mask to the stimulus did indeed weaken the GPE. Uniform-field flicker not only increased RT for the global letter but also decreased RT for the local letters, possibly because the masking of the low spatial frequency mechanisms had brought about a disinhibition of the high spatial frequency mechanisms involved in perceiving the local letters.

The involvement of high and low spatial frequency detection mechanisms can perhaps be most directly investigated using stimuli from which either the low spatial frequency or high spatial frequency components have been selectively filtered out. The study by Lovegrove, Lehmkuhle, Baro & Garzia (1991) compared standard compound letter stimuli with compound letters which have had their high spatial frequency components filtered out by the use of a diffusing screen, giving the stimuli a blurred appearance. These filtered stimuli produced a stronger GPE than the standard unfiltered stimuli, chiefly because the RT for the local letters was increased in the filtered condition. It seems that the lack of high spatial frequency information in the filtered stimuli made the perception of the local elements more difficult.

A related study by Badcock, Whitworth, Badcock and Lovegrove (1990) compared the RTs produced by standard compound letter stimuli with versions of the same stimuli which had the low spatial frequency components filtered out. The standard stimuli produced the usual GPE and inconsistency effects. The filtered stimuli, however, greatly increased the RT for the global letter while having little effect on RT to the local letters. The lack of low spatial frequency information in the filtered stimuli appears to have a selectively detrimental effect on the perception of the global letters. (In this experiment the inconsistency effect also disappeared when the filtered stimuli were used.)

CHAPTER 7.

7. THE ROLE OF HIGHER ORDER PROCESSES IN THE GPE.

7.1 Arguments against the involvement of lower-order processes.

A number of researchers have argued against the proposal that the GPE is a reflection of low-level visual system processes by demonstrating that post-perceptual processes (eg., attention or response competition) may influence the magnitude of the effect.

However, some of these arguments are based on data about conflicts between inconsistent global and local level elements rather than the relative speed of response to global and local levels generally (eg., Boer & Keuss, 1982; Garner, 1983; Paquet & Merikle, 1988). These sort of data are really telling us about the inconsistency effect rather than the GPE. As we shall see in the next section, it is likely that higher-order cognitive processes are involved in the IE.

On the other hand, some of these arguments do deal with the relative response times between local and global level elements. Miller (1981), for example, has reported an experiment in which subjects were required to respond to the presence of a target letter in a compound letter stimulus. The target letter could appear in the global level only, the local level only, or both the global and the local levels. He found that subjects responded more quickly when the target letter was in the global level only than when it was in the local level only, which is consistent with previous findings. However, the subjects responded even more quickly when the target letter appeared in both the global and local levels. Miller (1981) suggests that this indicates that the low-level visual processes transmit information about the global and local levels at equal speeds to a single decision mechanism. When this decision mechanism has received enough information about the stimulus, it is able to make a decision about the presence or absence of the target letter. If the target letter is present at both global and local levels of the stimulus the decision mechanism receives confirmatory information from two sources, allowing it to make a decision sooner. Miller (1981) accounts for the RT advantage of the global-only target letter over the local-only target letters by proposing that the global information has "greater strength" (p. 1171) or "more salience or more attention-grabbing power than local information" (p. 1164).

However, such an explanation leaves unanswered the question of why the global information has such "attention-grabbing power". Information about the stimulus can only reach the decision-making mechanism by first going through the low-level sensory mechanisms. Some quality or property of the low-level sensory information about the global level must have some influence on this "salience" or "attention-grabbing power", and one of these properties is likely to be the relative speed of the transmission of information.

Navon (1981a) has pointed out that Miller's results (1981) may be explained by using a parallel model of low-level visual processing in which there is a partial temporal overlap in the processing of global and local information with the global information being processed slightly faster (or beginning a little earlier), rather than a serial model in which the processing of global information must be finished before local processing can begin. The model proposed by Navon is consistent with the hypothesis that the GPE it produced by temporal differences in the parallel transient and sustained sub-systems. If this model is correct, it is possible that some early information about the local level could be added to the almost complete information about the global level. In this case the subject may be able to respond more quickly to a target letter that is present in both global and local level of the stimulus, because the decision-making mechanism would still be receiving similar letter-identifying information from both sources, as proposed by Miller (1981). In a situation where the target is present at the global level only, the subject would probably have to wait until the information about the global level alone was complete before making a response.

Ward (1982) has reported experimental results which suggest that attentional factors may play a part in the GPE. In his series of experiments two compound letters were displayed consecutively. In half the trials subjects were required to identify the letters in either the global level or the local level of both compound letters stimuli. In the other half of the trials they had to identify the local letter in the first stimulus and the global letter in the second stimulus, or vice versa. The subjects responded more quickly in those trials in which their attention was directed to the same level in both stimuli, and responded more slowly in those trials in which their attention was divided between levels. Comparison between the undivided attention trials showed that global letters were responded to more quickly than local letters - the standard GPE. On the other hand, the response times to both global and local letters in the divided attention trials were, on average, roughly equal. Most interestingly, RT was faster when the subjects had to identify the local letters in an undivided (local-then-local) attention trial than when they had to identify the global letter in a divided (local-then-global or global-then-local) attention trial.

Ward (1982) suggests that the longer response times for the divided attention tasks are the result of the necessity to switch from one attention state to another during the tasks. This could explain why response times to local letters in undivided attention trials were faster than response times to global letters in divided attention trials. However, while Ward's experiments demonstrate that attentional conflicts can affect the eventual response times to the global and local levels of a stimulus, they do not necessarily disprove the basic principle of global precedence in the low-level processing stages. Ward's results (1982) for undivided attention tasks consistently produced a standard GPE. After the complication of divided attention was introduced the RTs for both global and local levels increased quite dramatically and the

GPE disappeared. Presumably the difference in RTs between the undivided and divided attention tasks represents the time taken to resolve the attentional conflict, and this additional time is likely to have obscured the temporal differences produced by any underlying GPE.

There is also some evidence that selective attention can facilitate responses to a particular spatial frequency. Shulman and Wilson (1987) asked subjects to detect the presence of briefly presented gratings while they were simultaneously performing a standard compound letter identification task. They found that subjects were able to detect simultaneously presented low frequency gratings more often when the subjects were asked to identify the global letter, and high frequency gratings were detected more often when subjects were asked to identify the local letters. Once again, this does not disprove the principle of temporal global precedence in low-level processing, but demonstrates that subjects may selectively attend to a particular level of the stimulus. (Of course, the contents of the non-attended level may still have some effect on responses to the attended level, as seen in the inconsistency effect.)

In summary, it can be said that when both the global and local levels of a stimulus are equally visible and are not subject to attentional conflicts then the GPE will be reliably found; and it is reasonable to conclude that the effect is produced by the temporal differences between the transient and sustained sub-systems. However, this does not preclude the possibility that higher-order cognitive factors, such as attention, may come into play after the lower-order visual processes have done their work, and so have some effect on the eventual response to the percept.

7.2 The role of higher-order processes in the inconsistency effect.

While it seems that the GPE is brought about chiefly by low level visual processes, there is some evidence that the inconsistency effect which often accompanies it may be more connected with higher-order processes. The fact that the IE does not consistently occur in conjunction with the GPE suggests that the two effects are produced by somewhat different processes.

The experiments reported above demonstrate that manipulating factors believed to differentially affect the transient and sustained sub-systems may affect the GPE without having any affect on the IE. In Experiment 1(a) and Experiment 2, changing the density of the compound letter stimulus influenced the strength of the GPE but had no effect on the IE. The use of red, green and blue stimuli in Experiment 3 had a differential effect on the strength of the GPE, but had no effect on the IE. In Experiment 4 the strength of the GPE was affected by adaptation to a grating, but the IE was not. In addition, it was shown in Experiment 1(b) that a significant GPE will still occur in the absence of either consistent or inconsistent letters in the irrelevant level, so the presence of an IE is not necessary to the GPE.

On the other hand, it seems that manipulating higher-order cognitive factors may affect the inconsistency effect. Kimchi and Palmer (1985) found that the same set of compound stimuli could produce different patterns of responses when different instructions were given to the subjects. The stimuli which Kimchi and Palmer used were squares and rectangles made up of much smaller black and white squares ("checkerboard") or rectangles ("stripes"). When subjects were asked to identify the global form as either "square" or "rectangular" and the local forms as "checkerboard" or "stripes" no inconsistency effect was found. However, when another set of subjects were asked to identify the local forms, as well as the global forms, as "squares" or "rectangles" a inconsistency effect was found in both the global and local levels. It seems that the use of the same names to denote the features of both global and local levels increased the interference caused by the content of the irrelevant stimulus level. This effect is clearly the product of a higher-order cognitive process involving the naming of objects.

It must be remembered, however, that information about visual stimuli is made available to these higher-order processes via the lower-order visual processes, so it is likely that the functioning of lower-order processes will still have an influence on the IE. Hughes (1986) found that an IE (and a GPE) could be produced using compound gratings as stimuli. The compound grating consisted of a low frequency sine-wave grating and a high frequency sine-wave grating, which could be regarded as the equivalents of global- and local-level targets respectively. Each of these two component gratings could be vertically or horizontally oriented, with the two gratings being either of the same orientation (consistent) or different orientations (inconsistent). Subjects were asked to identify the orientation of the grating at the target level. Response time to the high frequency grating increased in the presence of an inconsistently oriented low frequency grating, but responses to the low frequency grating was not affected by the orientation of the high frequency grating. Hughes suggests that the IE in this example is produced by the inhibition of the sustained sub-system by the transient sub-system. The greater amount of inhibition in the case of inconsistent stimuli might be produced by orientation-sensitive cortical cells which are known to be inhibited by the presence of an orthogonally-oriented grating (Morrone, Burr & Maffei, 1982).

Badcock, Whitworth, Badcock and Lovegrove (1990), using more conventional compound letter stimuli, have found that the IE may be decreased by filtering out the low spatial frequency components of the stimulus. However, they reject the idea that the IE in this case is produced by transient-on-sustained inhibition alone, because this would be expected to affect all local letters equally and not just those which conflict with the global-level letters. They suggest that the IE may be produced by a form of response competition at a higher cognitive level which is nevertheless influenced by temporal differences within the lower-order visual processes. Information about the global letter will be transmitted quickly to the cognitive decision-making mechanism via the transient sub-system, priming a response to that stimulus. Information about the local letter will be transmitted more slowly via the sustained sub-system. In cases where the local letter is the target, and the global letter is inconsistent with it, the response to the local letter may suffer from interference from the conflicting response-priming produced by the global letter.

In summary, it can be said that the inconsistency effect is not necessarily produced by the same processes that produce the GPE, but is more likely to be connected with higher-order cognitive processes. However, as information about the stimulus is provided for these higher-order processes by low-level visual processes, it is also likely that low-level visual processes play some part in the IE.

CHAPTER 8.

8. CONCLUSIONS.

The series of experiments reported here set out to answer five specific questions which were designed to explore the connection between low-level visual processes (such as spatial frequency channels) and the global precedence effect. They were based on the assumption that the strength and even the direction of the GPE may be affected by manipulating factors which are known to have an effect on the functioning of these lower-order processes. If the predicted effects of these manipulations could be demonstrated it would be strong evidence in favour of the involvement of low-level visual processes in the GPE. The results may be summarised as follows:

(i) Martin (1979) found that the GPE was not inevitable but depended on stimulus sparsity. This was not consistent with the hypothesis that the GPE is a reflection of lower-order visual processes. Experiments 1(a) and 1(b) repeated Martin's experiment using consistently sized stimuli and more appropriate non-central presentation positions for the stimuli, and found a GPE for both densely and sparsely configured stimuli. However, stimulus density had no effect on the inconsistency effect.

(ii) Experiment 1(b) tested whether the GPE occurred in the absence of a concomitant inconsistency effect by using neutral symbols (rectangles) instead of letters in the non-target level of the compound figure stimulus, so that the non-target level is never "consistent" or "inconsistent" with the target level letter. A significant GPE was still found, indicating that the GPE and the IE are not necessarily the product of the same processes.

(iii) Experiment 2 used compound letter stimuli with equally visible global- and local-level letters to see if this affected the GPE. The GPE was found, although it was weaker and not statistically significant in the case of sparse stimuli, possibly due to the small sample size. Once again, stimulus density had no effect on the IE.

(iv) Experiment 3 investigated the effect of wavelength on the GPE by using colour stimuli. The low-level visual processing hypothesis of the GPE predicted that blue stimuli would produce a stronger GPE than red stimuli. This prediction was confirmed. Stimulus colour had no effect on the IE.

(v) Experiment 4 investigated the effect of spatial frequency and colour adaptation on the GPE. The low-level visual processing hypothesis of the GPE predicted that adaptation to a red grating would affect the GPE by reducing sensitivity to stimuli of a similar spatial frequency and colour. It was found that adaptation to the relatively low spatial frequency grating weakened the GPE by increasing response times to the global-level letter. However, adaptation to the colour red had no differential effect on responses to red or green stimuli, possibly because a relatively low spatial frequency adaptation grating was used. Adaptation to the grating had no effect the IE.

Taken together, the results of these experiments indicate that low-level visual mechanisms such as spatial frequency channels have a significant involvement in the GPE. This necessitates a revision of those positions which have argued that the GPE is primarily a higher-order cognitive effect. It does not eliminate the possibility of the invovement of higher-order processes in the GPE in some situations, but shows that their functioning must be limited by the output of lower-level mechanisms.

On the other hand, the present experiments provide evidence that the inconsistency effect is not systematically related to the GPE, and may reflect a different mechanism. This mechanism appears to involve higher-order cognitive processes beyond the visual system.

REFERENCES.

REFERENCES.

Antes, J. R., & Mann, S. W. (1984) Global-local precedence in picture processing. Psychological Research, 46, 247-259.

Badcock, J. C., Whitworth, F. A., Badcock, D. R., & Lovegrove, W. J. (1990) Low-frequency filtering and the processing of local-global stimuli. Perception, 19, 617-629.

Baro, J. A., & Lehmkuhle, S. (1989) The effects of a luminance-modulated background on grating-evoked cortical potentials in the cat. Visual Neuroscience, 3, 563-572.

Baro, J. A., & Lehmkuhle, S. (1990) The effects of a luminance-modulated background on human grating-evoked potentials. Clinical Vision Science, 5, 265-270.

Blakemore, C., and Campbell, F. W. (1969) On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. Journal of Physiology, 203, 237-260.

Blakemore, C., Nachmias, J., & Sutton, P. (1970) The perceived spatial frequency shift: Evidence for frequency selective neurones in the human brain. Journal of Physiology, 210, 727-750.

Boer, L. C., & Keuss, P. J. (1982) Global precedence as a postperceptual effect: an analysis of speed-accuracy tradeoff functions. Perception and Psychophysics, 31, 358-366.

Bowling, A., Lovegrove, W., & Mapperson, B. (1979) The effect of spatial frequency and contrast on visible persistence. Perception, 8, 529-539.

Breitmeyer, B. (1975) Simple reaction time as a measure of the temporal response properties of transient and sustained channels. Vision Research, 15, 1411-1412.

Breitmeyer, B. (1992) Sustained and transient channels in vision: A review and implications for reading. In D. Willows, R. Kruk, & E. Corcos (Eds.), Visual processing in reading and reading disabilities. New Jersey: Lawrence Erlbaum Publishers.

Breitmeyer, B. G., Levi, D. M., & Harwerth, R. S. (1981) Flicker masking in spatial vision. Vision Research, 21, 1377-1385.

Breitmeyer, B., & Williams, M. (1990) Effects of isoluminant-background color on metacontrast and stroboscopic motion: Interactions between sustained (P) and transient (M) channels. Vision Research, 30, 1069-1075.

Broadbent, D. E. (1977) The hidden preattentive process. American Psychologist, 32, 109-118.

Campbell, F. W., Cooper, G. F., & Enroth-Cugell, C. (1969) The spatial selectivity of the visual cells of the cat. Journal of Physiology, 203, 223-235.

Campbell, F. W., Cooper, G. F., Robson, J. G., & Sachs, M. B. (1969) The spatial selectivity of visual cells of the cat and squirrel monkey. Journal of Physiology, 204, 120-121.

Campbell, F. W., & Robson, J. G. (1968) Application of Fourier analysis to the visibility of gratings. Journal of Physiology, 197, 551-566.

Cleland, D. B., Dubin, M. W., & Levick, W. R. (1971) Sustained and transient neurones in the cat's retina and lateral geniculate nucleus. Journal of Physiology, 217, 473-496.

DeValois, R. L., & DeValois, K. K. (1975) Neural coding of colour. In E. C. Carterette & M. P. Friedman (Eds.), Handbook of Perception, Vol 5., New York: Academic Press.

Dreher, B., Fukada, Y., & Rodieck, R. W. (1976) Identification, classification, and anatomical segregation of cells with X-like and Y-like properties in the lateral geniculae nucleus of old-world primates. Journal of Physiology, 29, 433-452.

Enroth-Cugell, C., & Robson, J. G. (1966) The contrast sensitivity of retinal ganglion cells of the cat. Journal of Physiology, 187, 517-552.

Garner, W. (1983) Asymmetric interactions of stimulus dimensions in perceptual information processing. In T. Tighe & B. Shepp (Eds.), Perception, Cognition and Development: Interactional Analyses (pp 1-38). Hillsdale, NJ: Erlbaum.

Gibson, E. J. (1965) Learning to read. Science, 148, 1066-1072.

Graham, N., & Nachmias, J. (1971) Detection of grating patterns containing two spatial frequencies: a comparison of single-channel and multiple-channel models. Vision Research, 11, 251-259.

Grice, G. R., Canham, L., & Boroughs, J. M. (1983) Forest before the trees ? It depends where you look. Perception and Psychophysics, 33, 121-128.

Gross, C. G. (1975) Inferotemporal cortex in vision. Progess in Physiological Psychology, 5, 77-123.

Hoffman, J. E. (1980) Interaction between global and local levels of a form. Journal of Experimental Psychology: Human percetion and Performance, 6, 222-234.

Hubel, D. H., & Wiesel, T. N. (1962) Receptive fields, binocular interaction, and functional architecture in the cat's visual cortex. Journal of Physiology, 160, 106-154.

Hubel, D. H., & Wiesel, T. N. (1965) Receptive fields and functional architecture in two non-striate areas (18 and 19). Journal of Neurophysiology, 28, 229-289.

Hubel, D. H., & Wiesel, T. N. (1968) Receptive fields and functional architecture of monkey striate cortex. Journal of Physiology, 195, 215-243.

Hughes, H. (1986) Assymetric interference between components of suprathreshold gratings. Perception and Psychophysics, 40, 241-250.

Hughes, H. C., Layton, W. M., Baird, J. C., & Lester, L. S. (1984) Global precedence in visual pattern recognition. Perception and Psychphysics, 35, 361-371.

Kaplan, E., Shapley, R. M., & Purpura, K. (1988) Colour and luminance contrast as tools for probing the primate retina. Neuroscience Research Supplement, 8, S151-S165.

Keppel, G. (1991) Design and analysis: A researcher's handbook. New Jersey: Prentice Hall.

Kimchi, R., & Palmer, S. E. (1985) Separability and integrality of global and local levels of hierarchical patterns. Journal of Experimental Psychology: Human Perception and Performance, 11, 673-688.

Kinchla, R. A., & Wolfe, J. M. (1979) The order of visual processing: "top-down", "bottom-up", or "middle-out". Perception and Psychophysics, 25, 225-231.

Koffka, K. (1935) Principles of Gestalt psychology. New York: Harcourt Brace.

Kuffler, S. W. (1953) Discharge patterns and functional organization on mammalian retina. Journal of Neurophysiology, 16, 37-68.

Kulikowski, J. J., & Tolhurst, D. (1973) Psychophysical evidence for sustained and transient detectors in human vision. Journal of Physiology, 232, 149-162.

Lamb, M. R., & Robertson, L. C. (1988) The processing of hierarchical stimuli: Effects of retinal locus, locational uncertainty and stimulus identity. Perception and Psychophysics, 44, 172-181.

Lennie, P., Trevarthen, C., Waessle, H., & Van Essen, D. (1990) Parallel processing of visual information. In L. Spillman & J. S. Werner (Eds.), Visual perception: The neurophysiological foundations. New York: Academic Press.

Leventhal, A. G., Rodieck, R. W., & Dreher, B. (1981) Retinal ganglion cell classes in the old world monkey: Morphology and central projections. Science, 213, 1139.

Livingstone, M., & Hubel, D. H. (1988) Segregation of form, colour, movement, and depth: Anatomy, physiology, and perception. Science, 240, 740-749.

Lovegrove, W., & Badcock, D. (1981) The effect of spatial frequency on color selectivity in the tilt illusion. Vision Research, 21, 1235-1237.

Lovegrove, W. J., Lehmkuhle, S., Baro, J. A., & Garzia, R. (1991) The effects of uniform field flicker and blurring on the global precedence effect. Bulletin of the Psychonomic Society, 29, 289-291.

Lovegrove, W., & Over, R. (1972) Color adaptation of spatial frequency detectors in the human visual system. Science, 176, 541-543.

Luna, D., Merino, J. M., & Marcos-Ruiz, R. (1990) Processing dominance of global and local information in visual patterns. Acta Psychologica, 73, 131-143.

Lupp, U., Hauske, G., & Wolf, W. (1976) Perceptual latencies to sinusoidal gratings. Vision Research, 16, 969-972.

Maffei, L., & Fiorentini, A. (1972) Retinogeniculate convergence and analysis of contrast. Journal of Neurophysiology, 35, 65-72.

Maffei, L., & Fiorentini, A. (1973) The visual cortex as a spatial frequency analyzer. Vision Research, 13, 1255-1267.

Maffei, L., & Fiorentini, A. (1977) Spatial frequency rows in the striate visual cortex. Vision Research, 17, 257-264.

Maffei, L., Fiorentini, A., & Bisti, S. (1973) Neural correlate of perceptual adaptation to gratings. Science, 182, 1036-1038.

Martin, M. (1979) Local and global processing: the role of sparsity. Memory and Cognition, 7, 476-484.

McCollough, C. (1965) Color adaptation of edge-detectors in the human visual system. Science, 149, 1115-1116.

Meyer, G., & Maguire, W. (1977) Spatial frequency and the mediation of short-term visual storage. Science, 198, 524-525.

Miller, J. (1981) Global precedence in attention and decision. Journal of Experimental Psychology: Human Perception and Performance, 7, 1161-1174.

Morrone, M. C., Burr, D. C., & Maffei, L. (1982) Functional implications of cross-orientation inhibition of cortical visual cells. Proceedings of the Royal Society, London, Series B, 216, 335-354.

Movshon, J. A. (1975) The velocity tuning of single units in cat striate cortex. Journal of Physiology, 249, 445-468.

Movshon, J. A., & Lennie, P. (1979) Pattern-selective adaptation in visual cortical neurones. Nature, 278, 850-852.

Navon, D. (1977) Forest before the trees: the precedence of global features in visual perception. Cognitive Psychology, 9, 353-383.

Navon, D. (1981a) Do attention and decision follow perception ? Comment on Miller. Journal of Experimental Psychology: Human Perception and Performance, 7, 1175-1182.

Navon, D. (1981b) The forest revisited: More on global precedence. Psychological Research, 43, 1-32.

Navon, D. (1983) How many trees does it take to make a forest ? Perception, 12, 239-254.

Navon, D., & Norman, J. (1983) Does global precedence really depend on visual angle? Journal of Experimental Psychology: Human Perception and Performance, 9, 955-965.

Pantle, A., & Sekuler, R. W. (1968) Contrast response of human visual mechanisms to orientation and detection of velocity. Vision Research, 9, 397-406.

Paquet, L., & Merikle, P. M. (1988) Global precedence in attended and nonattended objects. Journal of Experimental Psychology: Human Perception and Performance, 14, 89-100.

Parker, D., & Salzen, E. (1977) Latency changes in the human visual evoked response to sinusoidal gratings. Vision Research, 17, 1201-1204.

Petersik, J. T. (1978) Possible role of transient and sustained visual mechanisms in the determination of similarity judgments. Perceptual and Motor Skills, 47, 683-698.

Podrouzek, K. W., Modigliani, V., & Di Lollo, V. (1992) Lateral masking as a determinant of global dominance. Perception, 21, 705-716.

Pomerantz, J. R. (1983) Global and local precedence: selective attention in form and motion perception. Journal of Experimental Psychology: General, 112, 516-540.

Riggs, L. A., White, K. D., & Eimias, P. D. (1974) Encoding and decay of orientation-contingent aftereffects of colour. Perception and Psychophysics, 16, 535-542.

Schiller, P. H., & Malpeli, J. G. (1978) Functional specificity of lateral geniculate laminae of the rhesus monkey. Journal of Neurophysiology, 41, 788-797.

Schneider, W. S. (1988) Micro Experimental Laboratory: An integrated system for IBM PC compatibles. Behavior Research Methods, Instruments and Computers, 20, 206-217.

Selfridge, O. G. (1959) Pandemonium: A paradigm for learning. In Symposium on the mechanization of thought processes. (Vol. 1) London: HM Stationary Office.

Sestokas, A. & Lehmkuhle, S. (1986) Visual response latency of X- and Y-cells in dorsal geniculate nucleus of the cat. Vision Research, 26, 1041-1054.

Sestokas, A. Lehmkuhle, S., & Kratz, K. (1987) Visual latency of ganglion X- and Y-cells: A comparison with geniculate X- and Y-cells. Vision Research, 27, 1399-1408.

Shapley, R., Kaplan, E., & Soodak, R. (1981) Spatial summation and contrast sensitivity of X and Y cells in the lateral geniculate nucleus of the macaque. Nature, 292, 543.

Shapley, R., & Perry, V. H. (1986) Cat and monkey retinal ganglion cells and their visual functional roles. Trends in Neurosciences, 9, 229-235.

Shulman, G. L., Sullivan, M. A., Gish, K., & Sakoda, W. J. (1986) The role of spatial frequency channels in the perception of local and global structure. Perception, 15, 259-273.

Shulman, G. L., & Wilson, J. (1987) Spatial frequency and selective attention to local and global information. Perception, 16, 89-101.

Titchener, E. B. (1915) A Beginner's Psychology. New York: Macmillan.

Tolhurst, D. (1973) Separate channels for the analysis of shape and movement of a moving stimulus. Journal of Physiology, 231, 385-402.

Vassilev, A., Manahilov, V. , & Mitov, D. (1983) Spatial frequency and the pattern onset-offset response. Vision Research, 23, 1417-1422.

Vassilev, A., & Stomonyakov, V. (1987) The effect of grating spatial frequency on the early VEP-component CI. Vision Research, 27, 727-729.

Ward, L. M. (1982) Determinants of attention to local and global features of visual forms. Journal of Experimental Psychology: Human Perception and Performance, 8, 562-581.

Watson, A. B., & Nachmias, J. (1977) Patterns of temporal interaction in the detection of gratings. Vision Research, 17, 893-902.

Wiesel, T. N., & Hubel, D. H. (1960) Receptive fields of ganglion cells in the cat's retina. Journal of Physiology, 153, 583-594.

Wiesel, T. N., & Hubel, D. H. (1966) Spatial and chromatic interactions in the lateral geniculate body in the rhesus monkey. Journal of Neurophysiology, 27, 1115-1156.

Williams, M., Breitmeyer, B., Lovegrove, W., & Gutierrez, C. (1991) Metacontrast with masks varying in spatial frequency and wavelength. Vision Research, 31, 2017-2023.

APPENDICES.

APPENDIX A

Data for Experiment 1(a).

Median response times (msec.), for each subject.

DENSE

S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	554.5	537.0	572.0	715.5
2	494.0	511.5	563.5	652.0
3	490.5	476.0	494.0	644.0
4	565.0	614.0	685.0	767.0
5	473.5	462.0	559.5	739.0
6	747.0	815.0	754.5	898.0
7	543.0	543.0	637.5	705.0
8	529.5	535.0	794.0	815.0
9	544.0	546.0	582.0	700.0
10	624.0	622.0	761.0	745.5
11	579.5	553.0	821.0	803.0
12	862.0	774.0	850.0	811.0
13	441.0	447.0	498.0	580.0
14	461.5	485.5	573.0	609.5

SPARSE

S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	561.0	617.0	635.0	659.0
2	496.5	494.0	558.0	673.0
3	470.0	491.0	532.5	579.5
4	609.0	599.0	632.5	667.5
5	476.5	522.5	528.0	674.5
6	908.5	970.0	730.0	988.5
7	564.0	532.5	592.0	658.5
8	619.5	612.0	703.5	725.0
9	651.5	707.5	628.0	675.5
10	621.5	614.5	688.5	739.0
11	592.5	576.5	841.0	923.5
12	706.0	644.5	633.0	745.0
13	461.5	488.0	484.0	552.0
14	452.0	432.5	553.5	605.5

APPENDIX A *(cont.)*

Data for Experiment 1(a).

Analysis of Variance Table.

Source	d.f.	M.S.	F	*p*
Main Effects:				
A *(Target letter level)*	1	281201.29	27.22	.0002
B *(Letter consistency)*	1	46863.22	15.99	.0015
C *(Density)*	1	36.57	.01	.9394
Interactions:				
A x B	1	37303.00	48.32	.0000
A x C	1	17176.51	8.45	.0123
B x C	1	315.57	.42	.5267
A x B x C	1	1.08	.00	.9771
Error:				
S *(Subjects)*	13	79555.44		
A x S	13	10329.68		
B x S	13	2930.97		
C x S	13	6091.67		
A x B x S	13	771.99		
A x C x S	13	2033.75		
B x C x S	13	745.92		
A x B x C x S	13	1267.17		
Simple Main Effects:				
A at C_2 *(Sparse)*	1	79803.51	12.91	$< .01$
Error	18	6181.72		
B at A_1 *(Global)*	1	272.97	.51	$> .05$
B at A_2 *(Local)*	1	83778.22	45.25	$< .01$
Error	19	1851.48		

APPENDIX B

Data for Experiment 1(b).

Median response times (msec.), for each subject.

S	Dense Global	Dense Local	Sparse Global	Sparse Local
1	410.0	537.0	442.0	553.5
2	477.5	536.5	461.0	524.0
3	600.5	687.0	572.0	651.0
4	494.0	599.0	485.0	544.0
5	876.0	880.0	873.0	1001.0
6	505.0	570.0	543.0	591.5
7	488.5	633.5	536.5	599.5
8	578.5	724.0	629.0	683.5
9	473.5	606.0	534.5	521.0
10	531.0	762.0	583.0	771.0
11	546.0	662.5	569.0	564.0
12	436.0	586.0	460.5	525.0
13	410.0	552.0	480.0	538.5

APPENDIX B *(cont.)*

Data for Experiment 1(b).

Analysis of Variance Table.

Source	d.f.	M.S.	F	*p*
Main Effects:				
A *(Target letter level)*	1	111508.92	65.31	.0000
B *(Density)*	1	105.31	.12	.7385
Interactions:				
A x B	1	7155.77	6.06	.0299
Error:				
S *(Subjects)*	12	51883.26		
A x S	12	1707.33		
B x S	12	902.30		
A x B x S	12	1180.59		
Simple Main Effects:				
A at B_2 *(Sparse)*	1	31084.65	21.53	$< .01$
Error	23	1443.96		

APPENDIX C

Data for Experiment 2.

Median response times (msec.), for each subject.

DENSE

S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	492.5	510.0	758.0	638.0
2	408.0	433.5	501.0	585.5
3	493.0	383.0	524.5	614.0
4	539.5	487.5	565.0	593.0
5	388.5	459.0	580.0	686.0
6	661.5	657.5	1266.0	1355.5
7	500.5	510.5	795.0	714.5
8	441.0	420.5	637.0	767.0

SPARSE

S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	531.5	538.0	526.0	630.0
2	461.5	468.0	481.0	475.0
3	491.5	559.0	443.0	530.0
4	581.5	588.0	644.0	584.0
5	475.0	543.0	544.0	596.0
6	775.5	695.5	1311.5	1230.0
7	532.0	526.0	679.0	729.5
8	490.0	503.5	662.0	629.5

APPENDIX C *(cont.)*

Data for Experiment 2.

Analysis of Variance Table.

Source	d.f.	M.S.	F	*p*
Main Effects:				
A *(Target letter level)*	1	512566.50	7.93	.0260
B *(Letter consistency)*	1	3284.72	1.64	.2413
C *(Density)*	1	116.91	.08	.7911
Interactions:				
A x B	1	2749.69	3.05	.1243
A x C	1	54085.32	55.76	.0001
B x C	1	75.47	.02	.8834
A x B x C	1	2030.63	.67	.4409
Error:				
S *(Subjects)*	7	213016.20		
A x S	7	64673.33		
B x S	7	2004.36		
C x S	7	1543.60		
A x B x S	7	902.09		
A x C x S	7	970.02		
B x C	7	3260.30		
A x B x C x S	7	3043.66		
Simple Main Effects:				
A at C_2 *(Sparse)*	1	117007.15	3.57	> .05
Error	7	32821.68		

APPENDIX D

Data for Experiment 3.

Median response times (msec.), for each subject.

RED

S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	541.0	522.0	570.0	651.5
2	506.0	498.5	566.5	629.5
3	868.5	756.0	1075.0	1106.5
4	466.0	479.0	633.0	618.5
5	493.5	470.5	607.0	654.0
6	582.0	583.5	634.0	662.5
7	429.0	459.0	568.0	655.0
8	524.0	557.5	610.0	703.0
9	554.0	692.0	557.5	626.0
10	556.0	527.0	695.0	795.5
11	635.5	672.5	714.0	883.0
12	490.0	450.5	556.0	599.0
13	507.5	454.0	509.0	598.5
14	541.5	539.0	656.0	687.0

GREEN

S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	514.5	485.0	599.0	698.5
2	530.5	480.0	564.5	653.0
3	709.5	887.0	921.0	988.5
4	508.5	508.0	628.0	643.0
5	491.5	468.0	600.5	623.5
6	609.0	627.5	645.0	684.0
7	461.5	421.5	543.5	627.0
8	548.0	554.0	635.0	707.0
9	564.0	593.0	604.0	652.5
10	559.0	538.5	655.0	765.0
11	630.0	626.0	786.0	811.0
12	456.5	476.0	528.5	622.5
13	477.5	469.0	511.0	611.0
14	595.5	573.0	624.5	660.0

APPENDIX D *(cont.)*

Data for Experiment 3.

Median response times (msec.), for each subject.

	BLUE			
S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	511.0	499.5	583.5	634.5
2	518.0	494.0	585.5	662.5
3	688.5	786.5	1092.5	980.0
4	481.0	480.0	658.0	668.5
5	461.0	468.5	551.5	657.0
6	575.5	624.5	656.0	680.5
7	446.0	465.5	587.0	698.0
8	543.5	603.0	674.5	692.5
9	535.0	554.0	652.5	654.5
10	513.0	565.0	700.0	706.0
11	633.0	571.0	722.5	846.0
12	506.5	472.0	609.5	696.0
13	484.5	449.5	573.5	613.0
14	538.0	518.0	653.5	718.0

APPENDIX D *(cont.)*

Data for Experiment 3.

Analysis of Variance Table.

Source	d.f.	M.S.	F	p
Main Effects:				
A *(Target letter level)*	1	709345.07	91.28	.0000
B *(Letter consistency)*	1	39024.76	66.20	.0000
C *(Color)*	2	316.78	.26	.7756
Interactions:				
A x B	1	31283.07	13.95	.0025
A x C	2	4793.42	4.35	.0234
B x C	2	246.38	.21	.8094
A x B x C	2	1049.48	.92	.4111
Error:				
S *(Subjects)*	13	118359.11		
A x S	13	7771.51		
B x S	13	589.51		
C x S	26	1234.76		
A x B x S	13	2242.90		
A x C x S	26	1101.27		
B x C x S	26	1155.92		
A x B x C x S	26	1140.87		
Simple Main Effects:				
A at C_1 *(Red)*	1	214397.44	64.49	< .01
A at C_2 *(Green)*	1	186302.57	95.63	< .01
Error	21	3324.68		
B at A_1 *(Global)*	1	214.33	.15	> .05
B at A_2 *(Local)*	1	70094.21	49.49	< .05
Error	19	1416.20		
Interaction Contrasts:				
A x C *(Red & Blue)*	1	2336.00	5.31	< .05
Error	13	440.31		
A x C *(Red & Green)*	1	247.00	0.36	> .05
Error	13	679.69		

APPENDIX E

Data for Experiment 4.

Median response times (msec.), for each subject.

	NO GRATING RED LETTERS			
S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	490.0	489.0	528.5	644.0
2	553.0	529.0	588.0	682.0
3	507.5	492.0	667.0	694.0
4	488.5	478.5	589.0	657.5
5	404.0	413.0	508.5	592.0
6	488.5	491.0	631.0	653.0
7	603.0	614.0	664.0	774.0
8	445.5	495.5	611.0	636.5
9	545.5	589.0	578.5	610.0
10	574.5	550.0	727.0	677.5
11	610.0	548.5	648.5	670.0
12	529.0	492.0	758.0	683.0
13	441.0	387.0	519.0	604.0
14	529.5	524.0	573.0	654.0
15	546.5	482.5	629.0	702.0
16	706.0	753.0	882.0	1006.5
17	493.5	450.0	505.0	600.0
18	441.0	447.0	546.5	669.0

APPENDIX E *(cont.)*

Data for Experiment 4.

Median response times (msec.), for each subject.

	NO GRATING GREEN LETTERS			
S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	537.5	610.0	593.0	692.0
2	545.5	508.0	580.0	666.0
3	520.5	511.0	678.5	708.0
4	491.0	515.0	556.0	625.0
5	434.0	382.0	485.5	555.0
6	497.0	482.5	636.5	649.5
7	681.5	616.0	698.5	722.0
8	482.5	460.0	621.0	633.0
9	557.0	600.0	558.0	611.0
10	670.0	663.0	737.5	826.5
11	580.0	590.0	669.0	690.0
12	503.0	527.0	736.0	668.5
13	394.5	390.0	584.5	602.5
14	559.5	528.0	575.5	686.5
15	526.5	511.0	610.0	716.0
16	713.5	742.5	851.0	918.5
17	430.0	433.0	515.5	619.0
18	423.0	464.5	574.5	673.0

APPENDIX E *(cont.)*

Data for Experiment 4.

Median response times (msec.), for each subject.

	WITH GRATING RED LETTERS			
S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	487.5	512.0	556.0	628.0
2	487.0	473.0	555.0	685.0
3	872.5	886.0	857.0	770.0
4	615.0	606.0	585.5	704.0
5	505.5	486.0	520.5	590.5
6	595.0	632.0	721.0	789.5
7	536.5	537.0	741.0	793.5
8	478.5	466.5	504.5	600.0
9	541.0	558.5	587.5	610.0
10	663.0	718.0	610.0	743.0
11	547.5	601.5	644.5	716.0
12	568.5	577.0	663.0	652.0
13	392.0	378.0	541.0	571.0
14	557.5	549.0	591.5	751.0
15	453.5	496.0	599.0	660.0
16	855.0	975.5	863.0	983.5
17	500.0	510.0	541.0	627.5
18	538.0	546.0	607.5	721.0

APPENDIX E (cont.)

Data for Experiment 4.

Median response times (msec.), for each subject.

	WITH GRATING GREEN LETTERS			
S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	524.5	543.0	550.5	646.5
2	512.5	478.5	587.5	647.0
3	832.5	800.5	827.0	809.5
4	592.5	585.5	619.0	639.5
5	491.5	517.0	550.0	620.5
6	673.0	623.5	714.5	732.5
7	632.5	582.5	648.0	769.5
8	478.0	503.0	642.5	599.5
9	543.5	524.5	609.0	610.5
10	682.0	663.0	660.0	661.0
11	580.0	628.0	669.5	669.0
12	564.5	610.0	645.5	690.0
13	384.0	394.5	523.5	637.0
14	593.0	695.5	600.0	648.5
15	499.0	473.5	580.0	684.5
16	890.0	1050.0	976.0	926.0
17	517.5	516.0	541.0	640.0
18	573.5	531.0	577.5	714.0

APPENDIX E *(cont.)*

Data for Experiment 4.

Analysis of Variance Table.

Source	d.f.	M.S.	F	*p*
Main Effects:				
A *(Target letter level)*	1	775946.53	145.86	.0000
B *(Letter consistency)*	1	69502.35	32.36	.0000
C *(Adaptation type)*	1	92056.25	4.83	.0420
D *(Letter colour)*	1	4851.13	5.47	.0318
Interactions:				
A x B	1	52866.68	21.75	.0002
A x C	1	40588.75	6.65	.0195
A x D	1	2800.01	2.58	.1266
B x C	1	1840.22	2.55	.1290
B x D	1	1001.28	1.53	.2324
C x D	1	10.13	.01	.9362
A x B x C	1	1168.06	1.62	.2202
A x B x D	1	1001.28	1.55	.2296
A x C x D	1	316.68	.38	.5460
B x C x D	1	1937.53	2.13	.1624
A x B x C x D	1			
Error:				
S *(Subjects)*	17	131422.34		
A x S	17	5319.91		
B x S	17	2147.89		
C x S	17	644.74		
D x S	17	886.27		
A x B x S	17	2430.23		
A x C x S	17	6099.98		
A x D x S	17	1084.76		
B x C x S	17	722.92		
B x D x S	17	652.87		
C x D x S	17	1532.60		
A x B x C x S	17	721.02		
A x B x D x S	17	644.74		
A x C x D x S	17	834.38		
B x C x D x S	17	908.53		
A x B x C x D x S	17	1208.24		

APPENDIX E *(cont.)*

Data for Experiment 4.

Analysis of Variance Table.

Source	d.f.	M.S.	F	*p*
Simple Main Effects:				
B at A_1 *(Global)*	1	566.66	.25	> .05
B at A_2 *(Local)*	1	121801.01	53.21	< .01
Error	34	2289.06		
C at A_1 *(Global)*	1	127419.87	10.14	< .01
C at A_2 *(Local)*	1	5196.06	.41	> .05
Error	27	12571.86		

APPENDIX F

Data for Experiment 2 (pre-test).

Minimum display durations (msec.) allowing subjects to achieve 80% accuracy.

DENSE

S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	10	10	10	10
2	10	10	40	10
3	10	10	70	10
4	100	40	100	100
5	10	10	10	10
6	10	10	70	100
7	10	10	100	100
8	10	10	40	40

SPARSE

S	Global Consist.	Global Incons.	Local Consist.	Local Incons.
1	10	10	10	10
2	10	10	10	10
3	10	10	10	10
4	10	10	10	10
5	10	10	10	10
6	10	70	40	100
7	10	10	100	100
8	10	10	40	100